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CORROSION CONDITION SURVEY OF U1020 MONTANA AVENUE OVERPASS-BILLINGS

FOR

MONTANA DEPARTMENT OF TRANSPORTATION

WJE No. 2000.2547

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INTRODUCTION

It was estimated by the Federal Highway Administration (FHWA) in 1997 that 101,518 bridges of the 581,562 bridges in the US were rated as structurally deficient, and the average cost to maintain these bridges will be $5.2 billion per year over the next 10 years [1]. The main source of such deterioration is corrosion of reinforcing steel in concrete.

Concrete possesses very high pH (12.5 to 13.5) by nature and reinforcing bars embedded in concrete form a stable thin oxide film (or passive film) on the surface in the presence of such a high alkaline environment. Therefore, reinforcing bars in concrete under this environment exhibit very low corrosion rates due to the passive film. However, there are two primary corrosion mechanisms involved with corrosion of reinforcing steel in concrete and both processes take place through destroying of the passive film (depassivation).

The first type of corrosion is induced by chloride ions which attack the passive film locally and spread the depassivated area with time. The chloride-induced corrosion of reinforcing bars usually results in pitting on the bar surface and can be intensive. After the US adopted a "bare road" policy in the 1960s by using deicing salts on the roads in winter, the rate of reinforced concrete structure deterioration, bridges in particular, has been steadily increasing. As the US infrastructure gets old, the problem becomes more serious.

The second type of corrosion is caused by carbonation of the concrete. This process involves a chemical reaction between calcium hydroxide in concrete and mainly carbon dioxide in the air which lowers the pH of the concrete. When the carbonation front reaches the reinforcing bar, the passive film on the bar starts to break down at pH 10-11 and eventually becomes depassivated.

When these two processes, singularly or in combination, is coupled with moisture and oxygen, corrosion of reinforcing bars in concrete proceeds at a rate which can be controlled by many factors such as dissolved oxygen availability, moisture content, resistivity of concrete, and temperature. The macrocell corrosion between macro-anode

and macro-cathode can be an important factor because the former is actively corroding at the rate of consuming electrons on the latter. Since concrete acts as a barrier to water, chloride ions, carbonation and oxygen, the depth of cover over the bars, cracks, and permeability of concrete are also important for resistance to corrosion in concrete.

Wiss, Janney, Elstner Associates, Inc. (WJE) was asked by Montana Department of Transportation to perform a comprehensive corrosion condition survey of the U1020 Overpass at Billings, Montana, because they are experiencing some damage due to corrosion of reinforcing bars. The overpass was originally constructed in 1960 and consists of separate eastbound and westbound bridges, which were 1,711 feet (522 m) long and designed to carry an AASHTO HS20 (MS18) load. Each bridge carries a 28-foot (8.5 m) wide roadway and the ADT in 1998 was 19,000. The eastbound bridge has seven prestressed beam spans on the west end, eight steel spans (each having four wide flange girders) in the middle, and another 17 prestressed beam spans on the east end (a total of 32 spans). The westbound bridge has the same configuration as the eastbound counterpart except that it has seven prestressed beam spans on the west end, six steel spans and 20 prestressed beam spans on the east end (a total of 33 spans). The length of the prestressed beam spans vary from 36 to 52 feet (11 to 16 m) and the steel spans range in length from 63 to 77 feet (19 to 23.5 m). Figure 1 shows an east face section view of the overpass.

In 1987, new decks were installed and minor repair work was made on the substructures. However, the overpass received a Sufficiency Rating (SR) of 65.6 in the 2000 inspection due to the combination of deck geometry rating of 3, clearance under rating of 3, and superstructure and substructure ratings of 5. According to the inspection records pertaining to the overpass, progressive damages has been noticed on some areas of the structures since 1991 and more visible corrosion-induced damages started to show in approximately 1995.

The decks of the overpass have received a mixture of sodium chloride and sand as a deicing agent in the winter seasons since 1978 according to the record. In 1994, magnesium chloride ($MgCl_2$) was used for one winter and a calcium chloride mixture ($CaCl_2$) was used for the following two years. Between 1997 and 1998, a mixture of 32 percent $CaCl_2$ mixed with Ice Ban was applied until it was replaced with Liquid Armor, a

Dow Chemical Corporation product, last winter. The deicing agents have been responsible for a fast deterioration rate observed on some areas of the substructure components as the corrosive deicers seeped through the faulty rubber expansion joint seals.

The objectives of this condition survey were to (1) evaluate the current corrosion-induced damage condition; (2) identify the cause(s) and the level of chloride contamination; (3) project the remaining service life of the structures; and (4) recommend appropriate repair methods and corrosion protection for the structures.

SITE CONDITION SURVEY

WJE performed a 5-day condition survey of the structures from September 5 through 9, 2000. During the field evaluation, the following activities were conducted to gather the essential field data:

Visual Survey and Damage Mapping

A detailed visual examination of the entire structures was made in the first day of the fieldwork and the observations were recorded on an individual bent basis for both bridges. The components of the structures were classified as deck surfaces (top and underside), prestressed beams, steel girders, cast-in-place diaphragms under the deck joints, bent caps, columns and transverse beams across columns. Cracks, spalls and delaminations were recorded on the mapping sheets by their location and extent. Fortunately, there was a heavy rain shower during the survey such that leaking deck joint seals were also identified.

Depth of Cover Measurements

A digital magnetic reinforcing bar locator was used to locate the reinforcing bars and to estimate depth of concrete cover over the reinforcing bars, mainly on the bent caps and columns because they were experiencing more damage than the rest of the components. Approximately, 270 measurements were made at selected locations of the bent caps and columns. At the limited locations where the reinforcing bars were exposed,

the cover readings were verified with the visual measurements. These readings were analyzed later to determine their statistical distribution per component. Limited number of cover measurements was also made on the deck and prestressed beams.

Half-Cell Potential Measurements

The half-cell potentials (or corrosion potentials) were measured to investigate the thermodynamic corrosion tendency of the reinforcing according to ASTM C876 [2] "Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete." An electrical connection was made to an reinforcement and potentials were measured using a voltmeter with a 200 MΩ internal impedance by placing a copper-copper sulfate reference electrode (CSE) on a 3 feet x 3 feet (1 m x 1 m) grid of the deck sections and on the selected surface areas of a bent cap and two columns. For two prestressed beams, a 6-in. x 6-in. (15 cm x 15 cm) grid was used starting 2 in. away from the beam bottom and end. The selection of test areas was generally made close to the deteriorated areas. Figure 2 shows this work in progress over Span 5 of the eastbound deck (the dark spots on the deck surface correspond to the wetted grid points).

Corrosion Rate Measurement

The instantaneous rate of corrosion was measured in terms of corrosion current density (I_{corr}, $\mu A/cm^2$) with a Gecor 6 instrument at 47 locations of the bent caps, columns, deck and prestressed beams. Tests were performed at the areas with various physical conditions including sound areas with no visible damages. However, the majority of the tested areas exhibited some types of damage. The device uses the principle of linear polarization from the corrosion potential of reinforcing bar (s) at a particular location. The surface area of reinforcing bar(s) beneath the Gecor 6 sensor was estimated by the pacometer readings and review of the construction plans. Figure 3 shows a measurement setup over a column using the Gecor 6, sensor and cable.

The resistivity and corrosion potential at the test spot were also measured by the Gecor 6. These supplementary data were useful for the qualitative data analysis.

Carbonation Testing

Since phenolphthalein changes color from pink to no color at pH 9 or less, depth of carbonation was determined by spraying phenolphthalein onto the freshly exposed test surface, which were made by chipping or drilling the concrete. Approximately one dozen spots were tested for carbonation in the field. Core samples were also measured for carbonation depth in the laboratory.

Coring

A portable electrical coring machine was used to take 32 concrete core samples at selected locations representing various conditions of the structures. Almost half of the cores were taken with a 4-inch (10 cm) diameter core bit and the remaining cores with a 2-inch (5 cm) diameter bit. Some of the cores were taken through the reinforcing bars to extract them for visual examination and laboratory analysis.

LABORATORY ANALYSIS

In the laboratory, the selected cores were used to determine the chloride concentration gradients, carbonation depth, condition of the steel, and the concrete quality.

Chloride Analysis

A total of 14 cores were selected based upon their extraction location (structural element and spatial position within) and physical condition of the concrete (level of damage) prior to coring. The samples were prepared by cutting either 1/8 or 1/4 in. thick slices a minimum of two different depths and analyzing for acid-soluble chlorides according to ASTM C1152 [3] “Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete.” All concrete slices were pulverized for chloride analysis and titration. The full-depth chloride profile was determined by fitting chloride data obtained from different depths of each core. From this step, chloride surface concentration (Cs) and residual chloride concentration (Co) were estimated and the diffusion coefficient of chloride of the core was calculated using the Fick’s second law.

Petrographic Examination

Five cores (C4, C5, C9, C15 and C28) were used for petrographic examination to characterize the quality of concrete, according to ASTM C457 [4] "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System of Hardened Concrete" and ASTM C856 [5] "Standard Practice for Petrographic Examination of Hardened Concrete." Carbonation was also tested in the laboratory by splitting the field cores and applying phenolphthalein solution onto freshly exposed concrete surfaces.

TEST RESULTS AND DISCUSSION

Visual Observation and Characterization of Damage

During the visual survey, five types of distress were noted on the structures. They were characterized and recorded in the mapping sheets as discrete cracks, finer but multiple cracks concentrated in local areas (noted as multiple cracks), spalls, delaminations, and fine pattern cracking. All except the pattern cracking was considered corrosion-induced damage unless there was evidence to classify it otherwise. Table 1 lists the frequency of particular damage occurrence for individual components which include bent caps, columns, prestressed beams under deck, cast-in-place diaphragms just beneath deck joints between prestressed beams (designated as joint diaphragm) and the transverse beams connecting south and north columns. None of the abutments showed any visual deterioration so were excluded from this report.

In addition, actively leaking joints are noted in Table 1. They are identified by the adjacent prestressed beams beneath the visual leakage. Several isolated freeze-thaw damaged areas were also observed. They are noted on the data sheets included in the appendix but they are not included in the Table 1 because the areas were so few. The visual damage maps are included in Appendix A (for individual bents) and Appendix B (for prestressed beams and deck joints) and all damages are indicated schematically. These sheets also include approximate locations of coring and the nondestructive tests performed.

As shown in Table 1, 27 out of 32 bents (84 %) for the eastbound bridge and 28 out of 33 bents (85 %) for the westbound bridge exhibit some types of damage. Among

them, four (13 %) and nine (27 %) bents were experiencing more severe damage than the rest for the eastbound and westbound bridges, respectively. However, none of them appeared to jeopardize structural integrity. The overall condition of the structures can be classified as “good” considering the fact that they have been in the harsh northern service environment for approximately 40 years.

The visual survey was performed from the ground and the majority of damaged areas were not physically tested to determine the extent of corrosion and delamination. However, selected areas were thoroughly inspected and accessed using a lift truck. Therefore, the data contained in this report may underestimate the total extent of delamination associated with the other types of damage. Further discussion of the condition of each component is included in the following sections.

1. Bent Caps and Joint Diaphragms

As indicated in Table 1 and Appendix A, many bent caps exhibit localized corrosion-induced damage, primarily in the form of discrete cracking and spalling. Figure 4 shows the west face of the eastbound Bent No. 27 with a spall exposing a corroded reinforcing bar and an adjacent delaminated area. Localized areas of some caps contained multiple fine cracks and pattern cracking which was not quantified. However, the locations of these minor distresses are schematically presented in the figures in Appendix A.

Many cap surfaces exhibited water stains, either dry or wet, due to past or current water leakage through deck joint seals. Figure 5 shows an active leak on the east cap face of the westbound structure Bent No. 29 at prestressed beams 4-5. Figure 6 shows the close-up view of the leaking joint shown in Figure 5. It shows a corrosion-induced spall and cracks on the cast-in-place concrete diaphragms between prestressed beams 4 and 5. The last column in Table 1 lists the actively leaking sections identified during the rainy field survey days. More comprehensive information regarding leakage can be found in Appendix A. The physical condition of these diaphragms is described in Appendix B.

Figure 7 shows the data analysis results of the influence of face orientation on damage frequency for cracking and spalls on the eastbound and westbound bent caps. It characterizes the crack and spall frequency in percentage versus orientation of the cap face. The other forms of damages were excluded from the analysis because they constituted minor in occurrences. Figure 7 shows that almost identical numbers of cracks were observed on both east and west cap faces, while spalling is more frequent on the east face compared to the west face. Since the surface area on south and north faces (cap ends) is much smaller than that of east and west faces, as shown in Figure 7, they cannot be directly compared. The fraction of crack occurrence on south and north faces is comparable but spalling on the south face was more than twice as frequent compared to the north face.

When total surface area is considered in conjunction with the data in Figure 7, it can be concluded that the south/north faces are more susceptible to corrosion-induced damages than the east/west faces. This finding can be attributed to the fact that south/north faces are frequently exposed to weathering, especially rain, while most parts of the east/west faces are shielded by the deck. The cracks and spalls on the east/west faces are concentrated near the cap ends indicating that these are also influenced by the exposure conditions near the ends. In addition, the south face is more exposed to the sun and is likely exposed to larger temperature and moisture fluctuations and possibly more cyclic freezing. This may explain why the south face exhibits a much higher frequency of spalling compared to that of the north face

In at least one location, a contributing factor to cracking and corrosion-induced damage was the location of drainage pipes from the deck. Figure 8 shows an example of this situation observed during a rainy day. The water from the drainage pipe wetted the south cap end surface and traveled down along the edge of cap and column. A horizontal crack can be also seen near top of the cap end. When water contains deicing salts in winter seasons, it will introduce an even more corrosive environment than rainwater itself. When drainage pipes were located near columns or bents water discharged from the pipes was carried by the strong wind to wet the lower portion of the substructures, mainly columns.

2. Columns

As Table 1 shows, a total of 85 cracks and 17 of spalls were observed on the eastbound and westbound columns. Figure 9 shows the typical spalling condition on the column having corroded reinforcing bars exposed. It was taken at the south face of the south column of the eastbound structure Bent No. 27. The spalled areas were commonly associated with large cracks and shallow depth of cover. The other types of distress include multiple cracks, pattern cracking and delaminations as summarized in Table 1. Actual locations of individual damage are schematically presented in Appendix A.

Some column surfaces, particularly round ones, exhibited pattern cracking in local areas. The cracking appeared to be superficial in most areas and not related to corrosion-induced stress. The round columns for the eastbound Bent No. 14 exhibit extensive pattern cracking and large vertical cracks. The cause of this localized cracking is uncertain.

Figure 10 shows the relationship between column face and the frequency of crack and spall occurrence. The cracks developed more frequently on east/south/west faces compared to the north face and spalls were most frequent on south faces followed by west/north faces, even though the differences in occurrence among the faces may not be statistically significant for both damage cases. However, it is apparent that the north and east faces are the statistically least susceptible to crack and spall developments, respectively. It is likely that exposure conditions related to temperature, cyclic wetting and cyclic freezing may contribute to the amount of distress.

3. Prestressed Beams

Corrosion-induced cracks and spalls occurred mainly on the outside beams (either No. 1 or 5). Furthermore, all damaged areas were limited to the beam ends below the deck joints at the bearings, as indicated in the figures in Appendix B. The distress is primarily due to leakage through the joints with some secondary contribution due to the increased wet and dry exposures of the exterior surfaces.. A total of 41 beam-ends (approximately 8 %) are exhibiting either cracks or spalls or

both. Figure 11 shows an example of deteriorated beam-ends having cracks, rust stains, and small spalls. One beam at Bent No. 25 of the eastbound structure (as indicated in Table 1 and Figure 24B in Appendix B) had a seriously deteriorated beam end that should be repaired in the near future. This beam end is a good example of the progression of corrosion-induced deterioration of the prestressed beam seats if the joint leakage is not stopped. Spalling and splitting of the concrete has occurred along the horizontal plane of the lower prestressing tendons. This is occurring in a region of low stress, however, the beam seat is upset and bearing may be lost. Repair of this type of damage normally includes attaching a new steel bearing seat to the face of the bent to support the beam away from its damaged end. If desired, further analysis and recommendations for structural repairs can be provided.

4. Deck

The 13-year old deck shows no sign of corrosion-induced damage. However, the undersides of the bridges contain numerous cracks as shown in Figure 12. Most of the cracks are transverse and have efflorescence making them clearly visible. The frequency of the transverse as well as longitudinal cracks along the length for both bridges is presented in Figure 13. Slightly more than 1,000 transverse cracks were counted on underside of each bridge. On average, each span contains more than 30 transverse cracks and approximately one longitudinal crack. Upon wetting of top deck surface by rain, some of the cracks showed signs of water transmission within several hours confirming the cracks are though-deck and leak.

Figures 14 and 15 show the top deck surface conditions of Span 5 and Span 25, respectively. The chalk lines shown in the photographs are the locations of visible cracks on the surface and they indicate the large number of cracks present in the studied areas.

Use of epoxy-coated reinforcing steel bars (ECRs) for both top and bottom reinforcement mats should be credited for the lack of corrosion-induced damage despite the large number of leaking cracks and the heavy deicing salt applications that have caused extensive corrosion-induced damage of the black steel beneath leaking joints. The extracted epoxy-coated reinforcement (ECR) from the deck was in

excellent condition and without any distress due to corrosion. The benefit of having ECRs in both mats can be easily recognized when the performance of this bridge is compared to one we recently investigated in Dubuque, Iowa that has similar cracking problems but used the ECRs in the top mat only and black bars in the bottom mat. The underside of the Dubuque bridge started to show signs of corrosion due to corrosion of bottom reinforcing bars in the form of rust stains, cracking, spalling, and delamination. Apparently, deicing salts infiltrated through the cracks reaching the bottom bars and causing serious corrosion of the black bars. WJE is currently performing a series of tests to mitigate the corrosion problems and minimize the negative effects of the cracks by applying different repair materials including silane.

Even though the deck condition is currently excellent, periodic monitoring of the decks should be performed by means of nondestructive electrochemical methods and occasional destructive core extractions at crack locations to examine the ECRs for corrosion. Repair of sealing of the cracks should also be considered to extend its life. This is necessary for the longevity of the bridge decks because corrosion will eventually initiate at coating defects as the chloride concentration at the reinforcing bars increases with time. Chlorides infiltrate the concrete not only from the top surface but also from the crack surfaces. Therefore, repair of sealing of the cracks is even more important.

5. Transverse Cross Beams between Columns

The lower cross beams of some bents were buried underground and they are not exposed. As data listed in Table 1 and Appendix A indicate, only minor damages were observed on the lower cross beams.

Depth of Cover

Figures 16 and 17 show the cumulative distributions of the depth of cover data for the bent caps and columns, respectively. They also contain the regression curve fits with the corresponding equations. It is reasonable to assume that the depth of cover data have normal distributions because the majority of the data points fell on the fitted straight lines

with a R of more than 0.97 (R is called the sample correlation coefficient and measures the strength of the linear association (perfect linear association when R = 1)).

The cumulative distribution (Figure 16) of the bent cap concrete cover data indicates that approximately 20 percent of the measurement locations are below the depth of cover (2.0 inch or 5.0 cm) specified in the construction plans. For the columns, approximately 50 percent of the measurement locations are below the specified depth of cover of 2.5 inch (6.3 cm) according to Figure 17. This 50% probability implies that the reinforcing cages fabricated to the minimum allowable concrete cover but were occasionally skewed when they were placed in the forms. Half of the bars had more than 2.5 inches of depth of cover at the expense of the other half of the bars the have less than the specified cover. This presents an interesting dilemma when fabricating cages for new construction. To consistently meet the specified minimum cover, the cages must be slightly undersized to allow for construction tolerances in placement. Much of the damage noted is at locations of low concrete cover. The exposed and corroded bars shown in Figure 9 have less than one inch (2.5 cm) of cover at the thinnest spot while the thickest part on the opposite face exceeded 4 inches (10 cm) cover.

Usually, spalled areas coincide with thin cover and this was particularly noticeable for the columns. Therefore, it can be concluded that the area with the thinnest concrete cover initiated corrosion first by carbonation and/or chloride penetration and led to ultimate failure of the concrete (spalling) due to corrosion of the reinforcing bars beneath at the presence of water and oxygen.

Half-Cell Potentials

The measured half-cell potentials were plotted as the equi-potential contour maps for various structural components as shown in Figures 18 through 22. Since many factors such as resistivity, temperature, concrete carbonation, and moisture content can influence the potential readings, relative variation of potentials within the tested area and the spacing between the contour lines were used to indicate areas of active corrosion.

A photograph and the potential contour map of the east cap face of eastbound Bent No. 25 are shown in Figure 18. The description of damage on this component is shown in Figure 24A in Appendix A. The tested area included a delaminated area and a

vertical crack. Carbonation testing was also performed at the delaminated area after loose concrete was removed. Test result indicated that carbonation exceed more than 1 in. (2.5 cm) depth along the fractured surface.

As expected, the electrical potential directly over the delaminated area did not indicate active corrosion, but the same map revealed the active corrosion spot adjacent to the delaminated area. Potentials directly over large delaminations or spalled areas will be less negative due to oxidation of the corrosion products and possibly poor electrical contact.

Figure 19(a) shows the cracked underside of the prestressed beam #5 also shown in Figure 11 and Figure 19(b) shows the potential contour map near the beam end. The active corrosion area near the cracked bottom section can be clearly seen as the most negative potentials in the contour map. According to the potential data and physical state of the beam, this particular beam is a good candidate for repair.

Figure 20(a) shows a photo of another prestressed beam #5 (showing south face) with the measurement grid marked on the surface and Figure 20(b) shows the corresponding the potential contour map. Again, the end of the beam was identified as having the most active corrosion (the most negative potential).

Figures 21 and 22 show the potential contour maps for selected deck areas in Span 5 and Span 25, respectively. The corresponding photographs of the decks are shown in Figures 14 and 15, respectively. Overall the potential range of the deck was more negative than the potential data taken at different components. The potential data on epoxy-coated reinforcing must be interpreted carefully since bar continuity may not be fully present. Changes in potential (steep gradients) may be a better indicator of possible corrosion than the actual values. As discussed previously, both decks contain many cracks and cracks can also influence potentials. Even though the extracted ECRs were in excellent condition and corrosion-free, the contour maps suggested that there is a possibility of corrosion initiation within the most negative potential locations.

The half-cell potential survey on the columns revealed that the potential readings were unreasonably positive such that they ranged from –0.143 to +0.130 V versus a CSE reference electrode (V_{CSE}) for the north column and –0.160 to +0.084 V_{CSE} for the south column of the eastbound Bent No. 27. Upon drilling to 1-inch (2.5-cm) depth to expose

the fresh concrete interior and uncarbonated concrete at two measuring spots, the subsequent potential readings dropped from +0.068 to –0.114 V_{CSE} and from +0.072 to –0.104 V_{CSE}, respectively. From this, it was concluded that carbonation was responsible for the exceptionally positive potential readings and further potential measurements were not made.

Rate of Corrosion

Figures 23 and 24 show the cumulative distributions of rate of corrosion data collected from the four different structural components. Actual data for corrosion rate measurements are listed in Table 3. Figure 23 contains the data for the bent caps and columns and both sets of data have similar distributions. Rate of corrosion data for the prestressed beams and decks are shown in Figure 24 and the regression fitted line for the decks is steeper than that of the prestressed beams indicating that decks were experiencing much slower rates of corrosion than the prestressed beam at the time of measurement.

The measured rates of corrosion are instantaneous for the confined reinforcing bar area at the time of measurement. Changes of the exposure conditions can greatly affect the corrosion rate. However, corrosion rate measurements are useful to get a snapshot of the corrosion condition and to compare areas of the structure. In general, corrosion rate of less than 0.1 $\mu A/cm^2$ is indicative of passive condition (very low rate of corrosion) and the rate between 0.1 to 0.5 $\mu A/cm^2$ is considered to be low to moderate corrosion. The moderate to high corrosion and very high corrosion can be expected when the instantaneous rates of corrosion range from 0.5 to 1.0 $\mu A/cm^2$ and greater than 1.0 $\mu A/cm^2$, respectively. However, changes of test conditions, particularly temperature and moisture content, can influence the readings significantly. A study [6] reported by Broomfield suggested that the rate of corrosion at the identical spot can vary by a factor of 100 or more.

According to Figures 23 and 24 with the inherent uncertainty of this technique in mind, it can be concluded that, approximately 30 percent of the tested bent caps, columns and prestressed beams was experiencing a low to moderate rate of corrosion at the time of measurement. This number might overestimate the actual condition of the structures

and may not represent the entire population in that the most test areas were selected from the deteriorated components. However, the result shown in Figures 23 and 24 indicate that active corrosion progresses at low to moderate rate in the tested sections of the bent caps, columns and prestressed beams and the corrosion process need to be mitigated by some means. The probability data in Figure 24 and actual condition of the deck agrees well such that the ECRs embedded in the entire deck sections remain passive without detectable damage.

The concrete resistances listed in Table 2 ranged from very low (0.8 ohms) to very high (170 ohms) and the columns tended to have higher resistances than the other components. High resistance is beneficial to slow corrosion problems in concrete because high resistance can limit how far the corrosion current travels in the concrete. About half of the resistance data indicate that resistance was not the limiting factor for the corrosion rate.

Study of Field Cores and Extracted Reinforcing Bars

A total of 32 field cores were taken from the four structural components: 11 from bent caps, eight from columns, five from prestressed beams and eight from two deck spans. Among them, seven cores were taken from the areas where a visible crack was present and three cores from delaminated areas. Cores were also removed from locations adjacent to the deteriorated areas and from sound areas. Table 3 summarizes the detailed information about each core.

A total of 13 cores contained 16 reinforcing bars whose size varies from #3 to #9. Five #5 ECRs were removed from the deck and exhibited an excellent condition without any sign of corrosion. In addition, another three deck cores had clean #5 ECR imprints at the fractured core bottoms. The condition of many of the black bars removed from support elements are also considered to be good even though individual black reinforcing bars varied from good, to light corrosion, to heavily corroded morphology depending upon location.

Table 3 describes the condition of the extracted bars and Figure 25 shows typical condition of three reinforcing bars with different degrees of corrosion.

Depth of Carbonation

Carbonation test results (maximum penetration depth) of the field cores are also listed in Table 3. Consistent with the field carbonation testing, the maximum depth of carbonation varies significantly from virtually zero to 2.0 in. (5 cm). The presence of fine cracks around the coarse aggregates in the hardened cement paste was mainly responsible for the deep carbonation fronts. Figure 26 shows two carbonation test results and one of them had a fully carbonated zone along the length of the core due to a large crack. This core revealed no carbonation away from the cracked surface (see pink color on the other side of the core fragment).

Averaged carbonation depth data indicate that bent caps (1.3 in. or 3.3 cm) and columns (0.9 in. or 2.3 cm) were experiencing deeper carbonation than the prestressed beams (0.5 in. or 1.3 cm) and the deck (0.5 in. or 1.3 cm). Corrosion can initiate without chlorides when carbonation reaches the depth of the reinforcing bars (cover of 2.0 in. (5 cm) or thicker) and depassivates the steel.

Petrographic Examination

Surface cracks were detected in all five cores examined and they were likely due to shrinkage of the cement paste. Carbonated paste around the cracks suggested that those cracks developed over time. None of the observed cracks passed through the coarse aggregates. Rounded gravel and natural siliceous sand were identified for the coarse and fine aggregates, respectively. There was no evidence of deleterious reaction between the aggregate and the cement paste.

The hardened cement paste contained numerous unhydrated cement particles and the water to cement ratio was estimated to be moderate to moderately low. Four cores contained air voids of 4 to 7 % volume of the concrete whereas the other core did not have air-entrained concrete. The complete petrographic examination report is provided in Appendix C.

Results of Chloride Analysis

Table 3 lists the actual chloride concentration at the different depths. The detection limit of chloride ions is about 0.008 weight percent (or < 80 ppm). Figures 27

through 30 show the chloride profiles of the field cores that were taken from the bent caps, columns, prestressed beams and deck, respectively. As expected, a high level of surface chloride contamination (more than 2,000 ppm) was observed near the top surface of the cores which were taken at deteriorated and cracked areas. However, the chloride concentration at the nominal concrete cover (a minimum of 2 in. (5 cm)) decreased considerably even in some of the cores extracted from the damaged areas. If the chloride threshold (Cth) for corrosion initiation of black reinforcing bars is assumed to be 300 ppm (or approximately 1.2 lb/yd^3 (0.71 kg/m^3)), only three out of 11 cores which were taken from the structures, except the deck, exceed this threshold at the 2 in. depth.

Chloride data from the deck cores indicate that the chloride concentration varied within the deck similar to the other structural components, depending on the condition of the concrete. One of three deck cores contained moderately high level of chlorides (1,250 ppm) even at 2 in. (5 cm) depth due to the presence of a crack, but the other two cores without cracks had low chloride contents at the reinforcing bar depths. One report [7] suggested that the chloride threshold for defect-free ECR could increase up to 3,000 ppm (or approximately 12.8 lb/yd^3 (7.6 kg/m^3)). WJE experimental data also suggest that much higher chloride threshold should be considered for high quality ECRs and Cth of 3,000 ppm is used in this study.

The cores extracted at the sound areas without any leakage exhibit flat chloride profiles along the depth, regardless of the coring location, because chloride contamination did not occur and the Cs was very low with respect to the inner chloride concentration (or detection limit of 80 ppm).

Since the acid-soluble chloride analysis reveals that overall chloride contamination was not extensive, water-soluble chloride analysis was not performed because the water-soluble chloride analysis usually yields less concentration than the acid-soluble one for the same sample. Water-soluble chloride may be more representative of the available chloride in concretes having aggregates with bound chloride.

Prediction of Remaining Service Life

Based upon chloride data, the chloride diffusion coefficient (D, in^2/year) of each core was calculated based upon solution to the Fick's law as follows:

$$\frac{Cx - Co}{Cs - Co} = 1 - erf\left(\frac{x}{2\sqrt{D \cdot t}}\right) \text{----- (1)}$$

The x and C_x represent a particular sampling depth in the core and chloride concentration at the depth, respectively. The *erf* is the Gaussian error function. Individual surface chloride concentrations (Cs) were determined by regression analysis of the chloride profiles shown in Figures 27 through 30 and reading the fitted values at x = 0 (top surface) for each core. If the calculated Cs was lower than the experimental chloride data measured at the closest to the top surface (most of them at 1/16 in. (1.6 mm)), the latter was used for the coefficient calculation. The chloride ion detection limit (80 ppm) was assumed to be the residual chloride content (Co) in the concrete. Time t (year) was used as 13 years for the deck (reinstalled in 1987) and 39 years for the rest of the components (built in 1961). After the chloride diffusion coefficient (D) was determined, the specific values of D, Cs, and Co were used to solve the Equation 1 for time t (in this case, time to corrosion initiation ($T_{initiation}$)) for each core. At the same time, the x and Cx in Equation 1 were replaced with the concrete cover and Cth of interest. The remaining life can be determined by adding a certain years for $T_{propagation}$ (assumed to be 3 to 6 years from corrosion initiation to damage development) to $T_{initiation}$.

In this case study, only the core with the highest chloride concentration was considered for each structural component with two different depths of cover cases. According to the calculation based upon experimental D, Cs, and Co of C1, the columns with less than 1.0 in. (2.5 cm) cover (x) will experience corrosion damage within 8.3 years ($T_{initiation}$ = 3.3 plus 5 years of $T_{propagation}$). The time to damage of the columns increases up to 25 years when cover of 2 in. (5 cm) or less is considered. The 2 in. (5 cm) depth of cover or less accounts for about 25 % of the column surface according to Figure 17.

For the bent cap case represented by C27, the remaining life of the cap with 1.0 in. (2.5 cm) or less cover is predicted to have corrosion problems within twenty years. The service life can be extended to more than 63 years when the concrete cover is more

than 2 in. (5 cm), which was represented by approximately 25 percent of the cap surface as shown in Figure 16. The prestressed beam and deck components, based upon C 17 (beam) and C7 (deck) experimental data, is predicted to have more than 75 years of service life.

Since the service life prediction is made with single core data, the generalization of these results should not be made. However, the outcome of the calculation demonstrates that the column is the critical component which will experience the most damages during the remaining service life of the structures under the current situation (continuation of chloride contamination at the leaking deck joints and existing chlorides in the concrete). On the other hand, the analysis indicates that the prestressed beams and the deck will be the least susceptible to the corrosion-induced damages except the beam ends directly exposed under the leaking joints.

The service life prediction was not made for carbonation-induced corrosion case because it is unlikely that the carbonation will be the dominant corrosion mechanism of the reinforcing bars in the structures.

RECOMMENDATIONS FOR REPAIRS AND CORROSION PROTECTION

The overpass structures have suffered some degree of corrosion-induced damage but generally maintain structural integrity. The following discusses the recommendations for problem areas.

Leaking Deck Joints

The primary cause of the corrosion-induced damage on the substructures is water leakage through faulty deck seals at some deck joints. The beams and columns away from currently or previously leaking joints had concrete that contains very low levels of chloride and virtually no distress. There is a clear relationship between leaking joints and the condition of the supporting structure. Deicing salt runoff appears to be the only source of chloride contamination on the substructures. Of course, carbonation could induce the corrosion damage to a much lesser extent at some future time. Among 12 currently leaking deck joints identified during the field survey and listed in Table 1, eight

bents have suffered various corrosion-induced damages which are candidates for repair. Four other bents with severe visual damage did not have leaking joints at the time of inspection, but they contained water staining indicating that the joints must have been repaired at some point. There were an additional four leaking joints that did not exhibit extensive damage on the substructures but only minor damage.

As recorded in Appendix B, some leakage took place within a limited range of the deck joint, say between only two prestressed beams, while others were over the entire joint. Also, there are deck joints that became moist on the underside but did not drip water. These joints should be also included in the scope of repair to prevent potential damage to the diaphragms and the prestressed beams. It is recommended that repair of the leaking joints should be a priority to ensure water tightness and thus prolong the service life of the overpass by stopping additional chloride contamination and reducing moisture exposure. The columns that show serious damage due to previous leakage but currently remain dry, had very low corrosion rate measurements. So by repairing the joint seals and reducing moisture, the corrosion and deterioration rates should decrease greatly. However, since some areas of the concrete are already contaminated with chloride, some continued corrosion must be anticipated.

Retrofit of Drainage Pipes from Deck

As discussed earlier, some drainage pipes are situated very close to the bent caps, and all the pipes were terminated too short from the deck so wetting of the concrete occurs in the presence of wind. Since water will contain deicing salts during the winter seasons, the pipe arrangement should be modified to divert the runoff away from the structure and concrete elements.

Repair of Damaged Sections

It is recommended that the damage at the beam seats be monitored and to anticipate some future repairs to restore the bearing seats. The spalled concrete does not pose a significant falling hazard as most of the deterioration is currently over areas of grass. Loose concrete could be removed by light chipping hammers. Also, the entire structure surface should be tested for delaminations that could not be identified from the

visual survey. Standard repairs should include squaring the edges of the patch, removing concrete to at least ¾ in. behind the reinforcing bars, sandblasting the bars and concrete surface and patching with drypack (small areas), acrylic modified concrete (medium areas), or form and cast concrete (large repairs). Preplaced aggregate and grout or shotcrete can also be used for large repairs. Spall repairs are not wide spread at this time and repairs can be deferred until after the joints are repaired (highest priority). It may be desirable to specify the repair materials to contain admixed corrosion inhibitors. In addition to the improved external appearance, the right patching material can protect the interior from the harsh service environments which cause progressive damage to the concrete and the reinforcing bars.

Sealing of cracks, beam ends, and exposed ends of the caps with a 100 percent silane-based sealer will also improve the durability of these elements. Cracks on the deck can be sealed using a high molecular weight methacylate (HMWM). A trial area is suggested prior to sealing the entire deck to ensure that the HMWM will adequately penetrate into and seal the deck cracks. Epoxy injection of tight deck cracks or the corrosion-induced cracks is usually not durable for more than a couple years and is not considered to be cost effective for this bridge.

Corrosion Protection

As discussed in an earlier section, chloride-bearing water has contaminated some sections of the overpass, and carbonation has reached some locations with low concrete cover to initiate corrosion of the reinforcing bars. Repairing and maintaining the joint seals and some cracking sealing should provide a significant reduction in the deterioration rate and improve the future prognosis for this structure. However, to extend the service life of this structure further, additional technologies are available. Due to its condition and location, this structure is a good candidate for evaluating various corrosion protection strategies that can then be incorporated on other structures throughout the state.

For these reasons, it is recommended that, after leaking joints and existing damages are repaired, the next step for providing longevity to the structures is to install

efficient corrosion protection systems. There are several viable options of both older and new technologies that show promise.

1. **Impressed Current Cathodic Protection (ICCP):**

   This technique employs a direct current (DC) to mitigate on-going corrosion by bringing the electrochemical state of the steel to a potential regime where corrosion rate is low or nil. A schematic of the ICCP system is shown in Figure 31. It involves application of a DC current from an anode made of noble metals to the embedded reinforcing bars (cathode) through the concrete that serves as the electrolyte.

   This technology has been used for more than 20 years and can be very effective to protect highway bridges and marine concrete structures from corrosion. However, this option involves somewhat extensive initial installation process of anode mesh (usually mixed metal oxide titanium), reference electrodes and DC rectifiers leading to relatively high initial cost. Also, this system requires repair of any spalled areas prior to installation of the anode mesh in order to prevent electrical short and ensure adequate transfer of protection current through the patched concrete. The possibility of overprotection must be controlled for the prestressed beams to prevent the high strength prestressed tendons from hydrogen embrittlement that can cause catastrophic brittle fracture of the tendons. Careful monitoring and maintenance of the system are also required for proper operation throughout the service life of the system. Maintenance of the ICCP systems has been the major problem for the practitioners and it is not an appropriate system for structures in remote areas. Even though ICCP is a very effective method to stop future corrosion, evaluation of this system on the 6th Street Overpass is not considered essential due to its maintenance difficulty, high initial cost, and limited applicability to remote structures.

2. **Sacrificial Anode Cathodic Protection**

   This method utilizes the same principle as the ICCP technique except that an active metal or alloy is used to create a natural potential difference between the anode and the cathode (reinforcing bars) for driving protection current through the concrete

instead of using an external DC rectifier. Currently, arc-sprayed metallic coatings are the popular choice for sacrificial anode cathodic protection of reinforced concrete structures. This involves spraying a 15 to 20 mils (381 to 508 μm) thick pure zinc or zinc-aluminum alloy metallic coating onto the concrete surface.

Main advantages of this technique include maintenance-free operation (operated by its own galvanic action), minimal preparation (sand blasting required but patching is not necessary) prior to coating installation and inexpensive initial cost. However, this system is particularly effective in high relative humidity environments and it does not work well on very dry concrete due to its high resistivity. This problem is being solved by spraying a hygroscopic solution known as Humactant™. Also, galvanic corrosion and atmospheric corrosion in air with time consume the coating so that periodic reapplication of coating may be necessary in every 5 to 20 years depending on the rate of coating consumption.

Another sacrificial cathodic protection system utilizes a pure zinc sheet with a conductive gel on it. It is manufactured and distributed by 3M with the trade name of Hydrogel. It has shown promising field performances in condominium repairs and other corrosion-damaged concrete structures. If the sheet can be securely attached to vertical surfaces such as bent caps and columns, this system is a good candidate for the overpass structures.

3. Migrating Corrosion Inhibitors

Corrosion inhibitors provide corrosion protection by two mechanisms: (1) a barrier to chloride ions, and (2) reduction of corrosion activity on the steel surface. There are many commercially available corrosion inhibitor products which can be applied to the concrete external surfaces and penetrate into concrete over time. The main advantages of this option are the lowest initial cost among the corrosion protection systems and it is simple to apply. New test methods have recently been developed to determine how deep the inhibitor penetrates into the concrete over time. A carbonation resistant and/or moisture-proof topcoat can be added to this system for additional protection. However, long-term effectiveness of the migrating corrosion inhibitors is not known yet due to the limited field performance data.

4. Electrochemical Chloride Extraction (ECE)

This technique is employed to remove chloride ions electrochemically from the concrete and surrounding the depassivated reinforcing steel surface. The principle of the ECE is the same as the cathodic protection shown in Figure 31 in that positive charges (current) are applied to the reinforcing bars from temporary external electrodes through which negatively-charged chloride ions are moved away from the bars to maintain charge neutrality. But, the ECE involves a much higher magnitude of applied current for shorter period of time (several weeks to months) compared to the impressed current cathodic protection system.

If the ECE is properly applied, repassivation of reinforcing steel is possible as a by-product because of hydroxide ions (OH^-) generation through water dissociation during the treatment. However, it is also known to have a potential risk of losing bond strength between the reinforcing bars and the concrete due to evolving hydrogen gas when excessive high applied current is used. For the same reason (hydrogen gas), this technology is not normally applicable to prestressed concrete because of the risk of hydrogen embrittlement.

Application of this technique on vertical surfaces or confined space may cause high operation costs associated with the extensive preparation necessary for installation of the temporary anode and water containment. This technique does not give a permanent solution to the corrosion problem unless the source of chlorides is removed and the long-term benefits of this method are still to be determined.

We believe that several treatments should be tried on limited areas prior to a full-scale installation to verify satisfactory field performance. Good candidates include two sacrificial anode cathodic protection systems (arc-sprayed zinc coating and Hydrogel) and corrosion inhibitors. The installation of these protection systems is easier and more cost-effective than the ICCP and ECE techniques. Due to the maintenance and other disadvantages, the ICCP is not recommended for this trial. The ECE holds promise and is recommended for a limited test area. The supporting elements and south column of the eastbound bent No. 25 (heavily contaminated with chloride) is a good candidate for this relatively expensive and elaborate option. Field

performance of the systems can be evaluated by periodic site monitoring as well as remote monitoring of embedded corrosion monitoring probes.

A large positive shift of half-cell potentials from the baseline potential is a clear indicator of a good performing corrosion inhibitor and the ECE. Penetration depth of migrating corrosion inhibitors in the extracted cores is another way of judging their effectiveness. For sacrificial anode corrosion protection systems, change of half-cell potential after 4-hour (or longer hours if necessary) depolarization process and the magnitude of protection current density are usually used for evaluating their performance.

We have also been in contact with an instrumentation firm from Great Britain that is currently monitoring a bridge in the UK similar to the study proposed for this bridge. They are interested in working with us in the United States. The goal would be to install corrosion monitoring instrumentation on each of the test locations, that would be directly linked to the Internet. Ultimately, engineers in the UK and MT DOT engineers (with a password) could at any time view the corrosion and environmental data of both the Billings and UK structures. This opens exciting possibilities related to bridge monitoring.

CONCLUSIONS

A 5-day field condition survey of U1020 Overpass in Billings, MT, was performed by WJE personnel. The following activities were performed: visual survey and damage mapping, depth of cover measurement, half-cell potential measurement, instantaneous rate of corrosion measurement, carbonation testing, and coring. A total of 32 cores were taken from four structural components, i.e., bent caps, columns, prestressed beams, and deck, with various physical conditions. The cores were analyzed in the laboratory for chloride concentrations, petrographic examination and carbonation testing. The following conclusions are made based upon the field survey and the laboratory analysis:

1. The overall condition of the structures can be classified as generally good considering the fact that they have been in the harsh northern service environment for approximately 40 years. The number of bents exhibiting corrosion-induced damages was 27 out of 32 bents (84 %) for the eastbound bridge and 28 out of 33 bents (85 %) for the westbound bridge. Among them, four (13 %) and nine (27 %) bents were experiencing more severe damage than the rest for the eastbound and westbound bridges, respectively. However, none of them appeared to jeopardize structural integrity. Only minor damages were observed on the lower cross beams. It was identified that 12 deck joints were actively leaking upon raining and eight bents beneath the leaking joints have suffered various corrosion-induced damages.

2. The south/north faces of the bent caps are more susceptible to corrosion-induced damages than the east/west faces. This finding can be attributed to the facts that south/north faces are frequently exposed to weathering, especially rain, while most parts of the east/west faces are shielded by the deck. Some drainage pipes are terminated too close to the south/north faces.

3. Cracks developed more frequently on east/south/west faces of the columns compared to the north face. The spalls observed on the columns were most frequent on south faces followed by west/north faces. It is likely that exposure conditions related to temperature, cyclic wetting and cyclic freezing may contribute to the amount of distress. Moreover, some column surfaces, particularly round ones, exhibited pattern cracking in local areas. The cracking appeared to be superficial in most areas and not related to corrosion-induced stress.

4. Some prestressed beams exhibited corrosion-induced cracks and spalls, mainly on the far outside beams. All damaged areas were limited to the beam ends below the deck joints at the bearings and the distress is primarily due to leakage through the joints. The beam No. 5 at Bent No. 25 of the eastbound bridge had a seriously deteriorated beam end that may need repair in the near future.

5. The 13-year old deck shows no sign of corrosion-induced damage. However, the undersides of the bridges contain numerous cracks. On average, each span contains more than 30 transverse cracks (overall more than 2,000) and approximately one longitudinal crack. Use of epoxy-coated reinforcing steel bars (ECRs) for both top and bottom reinforcement mats should be credited for the lack of corrosion-induced damage despite the large number of leaking cracks and the heavy deicing salt applications that have caused extensive corrosion-induced damage of the black steel in concrete beneath leaking joints.

6. Approximately 20 percent and 50 percent of the cover measurement locations on the bent caps (2.0 in. or 5.0 cm) and the columns (2.5 in. or 6.3 cm) are below the specified covers. Half-cell potential measurements identified the spots with high probability of active corrosion in the tested bent caps, prestressed beams and deck. The instantaneous rate of corrosion data indicate that corrosion progresses is progressing at low to moderate rates in approximately 30 percent of the tested areas and the corrosion process need to be mitigated by some means. About half of the resistance data indicate that resistance was not the limiting factor for the corrosion rate.

7. The carbonation testing revealed that the maximum depth of carbonation varies significantly from virtually zero to 2.0 in. (5 cm). Averaged carbonation depth of bent caps and columns were 1.3 in. (3.3 cm) and 0.9 in. (2.3 cm), respectively, and these numbers are deeper than that of the prestressed beams and the deck (both 0.5 in. or 1.3 cm). The presence of fine cracks around the coarse aggregates in the hardened cement paste was mainly responsible for the deep carbonation fronts.

8. Petrographic study of five field cores revealed that rounded gravel and natural siliceous sand were identified for the coarse and fine aggregates, respectively. There was no evidence of deleterious reaction between the aggregate and the cement paste. The hardened cement paste contained numerous unhydrated cement particles and the water to cement ratio was estimated to be moderate to moderately low. Four cores

contained air voids of 4 to 7 % volume of the concrete whereas the other core did not have air-entrained concrete. The overall condition of the extracted black bars removed from support elements are considered to be good even though individual black reinforcing bars varied from good, to light corrosion, to heavily corroded morphology depending upon location. All the extracted epoxy-coated reinforcing bars from the deck are in excellent condition without any sign of corrosion.

9. Acid-soluble chloride profile data show a large variation of chloride concentrations such that a high level of surface chloride contamination (Cs > 2,000 ppm) was observed near the top surface of the deteriorated and cracked cores and very low Cs was found for the sound cores. However, the chloride concentration at nominal concrete cover over reinforcing bars (a minimum of 2.0 in. or 5 cm) decreased considerably even in some of the cores extracted from the damaged areas.

10. According to the remaining service life calculation based upon the worst current condition, the column is the critical component which will experience damages within about eight years for the area with cover of 1.0 in. (2.5 cm). For the bent cap, the areas with 1.0 in. or less (2.5 cm) are estimated to have corrosion problems within twenty years. Both elements should give much longer service life for the thicker depth of cover cases. The prestressed beams and the deck will be the least susceptible to the corrosion-induced damages except the beam ends directly exposed under the leaking joints. The service life prediction was not made for carbonation-induced corrosion case because it is unlikely that the carbonation will be the controlling corrosion mechanism in the structures.

11. It was determined that chloride contamination of the concrete through the leaking deck joints was responsible for most corrosion-induced damages. To a much lesser degree, corrosion due to carbonation was likely to be the corrosion process that initiated at the areas with thin concrete cover.

12. It is recommended that leaking deck joints and short drainage pipes should be repaired to minimize the additional chloride contamination. It is further suggested that currently damaged areas should be repaired with appropriate methods and materials. To mitigate the on-going corrosion process, several corrosion protection systems are recommended for field trials on selected areas. These include impressed current cathodic protection, sacrificial anode cathodic protection, corrosion inhibitors, and electrochemical chloride extraction. Based upon the outcome of field trials, the most cost effective and best performing corrosion protection system can be identified for the overpass and implemented for the corrosion susceptible areas.

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Bent No.	Cap					Column					Prestressed Beam		Joint Diaphragm		Bottom Transverse Beam		Active Leakage Location
	Crack	Multiple cracks	Pattern cracking	Spall	Delamination	Crack	Multiple cracks	Pattern cracking	Spall	Delamination	Crack	Spall	Crack	Spall	Crack	Spall	
EB 2	1										1	1	1	1			
*** EB 3**	6	2												1			
EB 4	3												1				
EB 5	1	1									1		4	1			Beams 3-5
EB 6	3					2				1	1		2	1			
EB 7				1							2		1				
EB 8		1															
*** EB 9**	4	1		1		4	1		1								
EB 10			1			5		1									
EB 11	1					1		2									Beams 2-4
EB 13								2									
EB 14						2											
EB 15						4		1									
EB 16						3	1										
EB 18						2											
EB 19											1		1				
EB 21	2					2					3						
EB 22								1							1		
EB 23						2					1			1			
EB 24														3			
*** EB 25**	3			2	2	2			2		2		4	2			Beams 2-5
EB 26	1			1		1			2		1						
*** EB 27**	2			1	1	4			4				8	1			Beam 4-5
EB 28	1			1		8			1		2		6				
EB 29												1	3				
EB 30	3										1		4		4	1	Beams 1-5
EB 32	1			1							1		6	1			
EB Subtotal	**32**	**5**	**1**	**8**	**3**	**42**	**2**	**7**	**10**	**1**	**17**	**2**	**41**	**12**	**5**	**1**	**12 spots**

* These bents are experiencing more damages than the others and need to be repaired.

Table 1. Summary of Deteriorated Conditions of Structural Component

Bent No.	Cap					Column					Prestressed Beam		Joint Diaphragm		Bottom Transverse Beam		Active Leakage Location
	Crack	Multiple cracks	Pattern cracking	Spall	Delamination	Crack	Multiple cracks	Pattern cracking	Spall	Delamination	Crack	Spall	Crack	Spall	Crack	Spall	
WB 3	6			2							1		4				
WB 4						2					2		1				
WB 5	4		2								2		2				
WB 6													1	4			
WB 7	1										2			1			
*** WB 8**						5	2	1	2		1		3	1			Beams 1-4
WB 9							1										
*** WB 10**	3					3									1		Beam 1-2
WB 13						1		1									
WB 14	1																
WB 15	1					2					1						Beams 3-5
*** WB 16**	1					7											
*** WB 17**	7			4							2						
*** WB19**	5					7			1		2			2			Beams 3-5
WB 20	1																
*** WB 21**	4					1			1		2		1	1			Beam 4-5
WB 22	1			1											1		
WB 23		1															
*** WB 25**	1	1			1	3					1		1				
WB 26	1					1			1								
*** WB 27**	1		3			5		2			1		1				Beams 1-3
WB 28	4										2		1	1			
*** WB 29**	10					6		1	2		1	1	7	1			Beams 2-5
WB 30	1			1													
WB 31	2												1	1			
WB 32	3																
WB 33	2												3				
WB Subtotal	61	2	5	12	1	43	3	5	7	0	21	1	26	12	2	0	14 spots
EB + WB Total	**93**	**7**	**6**	**20**	**4**	**85**	**5**	**12**	**17**	**1**	**38**	**3**	**67**	**24**	**7**	**1**	**26 spots**

* These bents are experiencing more damages than the others and need to be repaired.

Table 2. Rate of Corrosion Data

ID	Measurement Location						Condition of Measurement Location		Measurement Data				Note
	Bound	Bent No.	Component	Face	x (ft.)	y (ft.)	Delamination	Crack	Rebar Size (Area, cm^2)	CR (uA/cm^2)	Corrosion Potential (V, CSE)	Resistance (kohms)	
CR 1	EB	P27	North Column	South	Center	1.6 from bottom	N	N	#8 (84)	0.024	0.090	74.0	
CR 2	EB	P27	North Column	North	Center	6.7 from bottom	N	N	#8 (84)	0.023	0.050	51.3	
CR 3	EB	P27	Cap	West	1.3 from south end	1.1 from top	N	N	#5 (52)	0.009	-0.221	5.3	Next to spalled area
CR 4	EB	P27	Cap	West	2.3 from south end	1.1 from top	Y	Y	#5 (52)	0.029	-0.283	1.9	Measured over a vertical crack
CR 5	EB	P27	Cap	West	3.4 from south end	1.1 from top	N	N	#5 (52)	0.004	-0.311	3.8	
CR 6	EB	P27	Cap	West	4.3 from south end	1.1 from top	N	N	#5 (52)	0.006	-0.129	23.8	
CR 7	EB	P27	South Column	South	2.0 from left edge	2.3 from bottom	N	N	#8 (84)	0.006	-0.334	22.9	
CR 8	EB	P27	South Column	East	2.0 from left edge	2.3 from bottom	N	N	#8 (84)	0.005	-0.347	12.1	Measured over paint
CR 9	EB	P27	South Column	West	2.0 from left edge	2.3 from bottom	N	N	#8 (84)	0.014	-0.083	46.9	
CR 10	EB	P27	South Column	North	2.0 from left edge	2.3 from bottom	N	N	#8 (84)	0.025	-0.015	51.7	
CR 11	EB	P25	South Column	South	2.0 from left edge	4.6 from bottom	N	N	#8 (84)	0.407	-0.419	1.0	Close to spalled and cracked area. Surface appeared to be wet. Core #1 was taken next to the measurment spot.
CR 12	EB	P25	South Column	South	2.0 from left edge	6.6 from bottom	N	N	#8 (84)	0.460	-0.399	2.3	Close to spalled and cracked area
CR 13	EB	P25	South Column	North	2.0 from left edge	6.3 from bottom	N	N	#8 (84)	0.008	-0.044	133.0	
CR 14	EB	P25	South Column	North	2.0 from left edge	3.3 from bottom	N	N	#8 (84)	0.010	-0.054	115.9	Surface appeared to be dry. Core #2 was taken next to the measurment spot.
CR 15	EB	P27	South Column	South	2.0 from left edge	2.3 from bottom	N	N	#8 (84)	0.080	-0.258	20.1	Rerun on CR 7 spot
CR 16	EB	P27	South Column	South	2.0 from left edge	6.4 from bottom	N	N	#8 (84)	0.080	-0.192	23.3	
CR 17	EB	P27	South Column	North	2.0 from left edge	2.3 from bottom	N	N	#8 (84)	0.033	-0.013	54.1	Rerun on CR 10 spot
CR 18	EB	P27	South Column	North	2.0 from left edge	6.4 from bottom	N	N	#8 (84)	0.007	-0.003	170.0	
CR 19	EB	P27	North Column	South	2.0 from left edge	1.6 from bottom	N	N	#8 (84)	0.025	0.083	70.3	Rerun on CR 1 spot
CR 20	EB	P27	North Column	North	2.0 from left edge	6.7 from bottom	N	N	#8 (84)	0.019	0.065	61.9	Rerun on CR 2 spot
CR 21	WB	P29	South Column	South	1.4 from left edge	2.3 from bottom	N	N	#8 (84)	0.340	-0.313	5.2	
CR 22	WB	P29	South Column	North	1.4 from left edge	2.3 from bottom	N	N	#8 (84)	0.073	-0.217	26.7	
CR 23	WB	P29	South Column	North	1.4 from left edge	6.4 from bottom	N	N	#8 (84)	0.108	-0.242	20.2	

Table 2. Rate of Corrosion Data

ID	Measurement Location						Condition of Measurement Location		Measurement Data				Note
	Bound	Bent No.	Component	Face	x (ft.)	y (ft.)	Delamination	Crack	Rebar Size (Area, cm^2)	CR (uA/cm^2)	Corrosion Potential (V, CSE)	Resistance (kohms)	
CR 24	WB	P29	South Column	South	1.4 from left edge	6.4 from bottom	N	N	#8 (84)	0.014	-0.281	5.7	
CR 25	No Data												
CR 26	WB	P29	South Column	East	0.8 from left edge	2.3 from bottom	N	N	#8 (84)	0.253	-0.331	2.5	
CR 27	WB	P29	South Column	East	0.8 from left edge	6.4 from bottom	N	N	#8 (84)	0.271	-0.333	1.1	
CR 28	WB	P29	South Column	North	Close to left edge	2.3 from bottom	N	N	#8 (84)	0.889	-0.404	1.6	Measured over a black stain & next to CR 22
CR 29	WB	P29	South Column	North	Close to left edge	6.4 from bottom	N	N	#8 (84)	0.281	-0.333	1.6	Measured over a black stain & next to CR 23
CR 30	WB	P29	Cap	East	5.6 from left edge	1.3 from top	Y	N	#9 (94)	0.030	-0.477	3.3	Wetted area by run-down water; Core #11 was taken at the spot; Bar moderately corroded.
CR 31	WB	P29	Cap	East	4.7 from left edge	4.0 from top	N	N	#9 (94)	0.153	-0.317	1.7	Wetted area by run-down water; Core #15 was taken at the spot; Bar lightely corroded.
CR 32	WB	P29	Cap	East	1.4 from left edge	2.3 from top	N	N	#5 (52)	0.068	-0.281	3.9	Core #13 was taken at the spot
CR 33	WB	P29	Cap	East	11.0 from left edge	1.8 from top	N	N	#5 (52)	0.236	-0.396	2.4	Measured over a water path
CR 34	WB	P29	Cap	East	4.7 from left edge	1.3 from top	N	N	#9 (94)	0.054	-0.420	2.3	Wetted area by run-down water; Measured over the same bar as CR 31.
CR 35	WB	P29	PS Girder #5	South	1.2 from west end	1.5 from bottom	N	N	#4 (42)	0.122	-0.273	2.0	
CR 36	WB	P29	PS Girder #5	South	3.2 from west end	1.5 from bottom	N	N	#4 (42)	0.049	0.089	51.9	
CR 37	WB	P29	PS Girder #5	South	1.7 from west end	0.2 from bottom	N	N	#4 (42)	0.023	-0.172	15.9	
CR 38	WB	P29	PS Girder #5	South	0.2 from west end	1.0 from bottom	N	N	#4 (42)	0.040	-0.284	3.6	
CR 39	EB	P25	PS Girder #5	South	1.2 from west end	1.5 from bottom	N	N	#4 (42)	0.154	-0.441	0.8	
CR 40	EB	P25	PS Girder #5	South	1.7 from west end	0.2 from bottom	N	Y	#4 (42)	0.178	-0.405	1.5	Measured over a horizontal crack
CR 41	EB	P25	PS Girder #5	South	3.2 from west end	1.5 from bottom	N	N	#4 (42)	0.050	0.003	64.5	
CR 42	EB	P6 - P7	Deck	Span 6	75.3 from EJ @ P5	9.0 from Curb	N	N	#5 (52)	0.028	-0.435	12.1	
CR 43	EB	P6 - P7	Deck	Span 6	93.3 from EJ @ P5	0.5 from Curb	N	N	#5 (52)	0.024	-0.337	16.8	
CR 44	EB	P6 - P7	Deck	Span 6	96.3 from EJ @ P5	9.0 from Curb	N	N	#5 (52)	0.024	-0.389	23.5	
CR 45	EB	P25 - P26	Deck	Span 25	3 from EJ @ P25	6.0 from Curb	N	N	#5 (52)	0.013	-0.505	23.0	
CR 46	EB	P25 - P26	Deck	Span 25	12 from EJ @ P25	9.0 from Curb	N	N	#5 (52)	0.012	-0.418	23.1	
CR 47	EB	P25 - P26	Deck	Span 25	30 from EJ @ P25	0.5 from Curb	N	N	#5 (52)	0.012	-0.352	17.8	

Table 3. Summary of Field Core Data

Core ID	Coring Location						Core Dimension		Condition of Coring Location		Extracted Rebar			Acid-soluble chloride content (wt. % by sample weight)									Max. Depth of Carbonation (in.)	Note
	Direction	Bent No.	Component	Face	x (ft.)	y (ft.)	Diameter (in.)	Length (in.)	Delamination @ depth	Crack (width, mils)	Cover (in.)	Size	Condition	0-1/8 in.	1/8-3/8 in.	1.0-11/8 in.	11/4-11/2 in.	11/2-15/8 in.	2.0-21/8 in.	21/2-23/4 in.	3.0 -31/8 in.	4.0 -41/8 in.		
1	EB*	P25	South Column	South	1.2 from left	4.6 from bottom	4.0	5 3/8 in 2 pcs	Y @ 1 1/4 in.	N		No bar		0.654			0.280					0.075	3/4	Next to spalled area & clsoe to active leakage
2	EB	P25	South Column	North	1.3 from left	3.2 from bottom	4.0	4 5/8	N	N		No bar			0.010		< 0.008			< 0.008			5/8	Dried area with no staining
3	EB	P5 - P6	Deck	Span 5	11 from EJ @ P5	5.4 from Curb	4.0	2 3/4	N	Y (16 @ 1/4 in., 3 @ 2 in.)	2 3/4	#5 (ECR)	Excellent										2 in @ crack (zero @ fresh surface)	Transverse crack over the bar
4	EB	P5 - P6	Deck	Span 5	20 from EJ @ P5	4.6 from Curb	4.0	5 1/2	N	Y	5 1/2	#5 Imprint	Clean										1.0	Over a pattern cracking/Used for petrographic exam
5	EB	P6 - P7	Deck	Span 6	72 from EJ @ P5	11 from Curb	4.0	2 3/4	N	Y (7 @ 1/4 in., 2 @ 2 in.)	2 5/8	#5 Imprint	Clean										1/4	Over a pattern cracking & on left wheel path/Used for petro-graphic exam
6	EB	P7 - P8	Deck	Span 7	132 from EJ @ P5	0.7 from Curb	4.0	6	N	N	3 3/4	#5 (ECR)	Excellent		0.094		0.037			< 0.008			1/2	Close to curb & the highest point (Selected as a control)
7	EB	P25 - P26	Deck	Span 25	40 from EJ @ P25	4.4 from Curb	4.0	2 1/2 in 2 pcs	N	Y (20 @ 1/4 in., 2 @ 2 in.)	2 3/8	#5 Imprint	Clean	0.329		0.138			0.125				N/A	Over a large transverse crack
8	EB	P25 - P26	Deck	Span 25	46.5 from EJ @ P25	0.6 from Curb	4.0	5 1/2	N	N	2	2 #5 (ECRs)	Excellent		0.127		0.040			< 0.008			1/2	Good area subjected to run-off and low side of curb
9	EB	P26 - P27	Deck	Span 26	57 from EJ @ P25	10 from Curb	4.0	5 1/2	N	Y (13 @ 1/4 in., 5 @ 2 in.)	2 1/2	#5 (ECR)	Excellent										0	Over a large transverse crack /Used for petro-graphic exam
10	EB	P27 - P28	Deck	Span 27	3.7 from EJ @ P27	7.3 from Curb	4.0	5 1/2	N	N	3	#4	Excellent										0	Center of the right lane
11	WB*	P29	Cap	East	5.6 from left	1.3 from top	4.0	5.0 in 2 pcs	Y @ bar level	During coring	1 1/4	#9	Moderately corroded	0.197		0.032						0.046	2.0	Over heavy staining/leakage area
12	WB	P29	Cap	East	6.0 from left	1.0 from top	4.0	1 3/4 in 5 pcs	N	Y (10 @ 1/4 in)	1 5/8	#5	Heavily corroded										1 1/2	Over heavy staining/leakage area
13	WB	P29	Cap	East	1.3 from left	2.3 from top	4.0	5 3/4	N	N	1 1/8	#5	Moderately corroded										1.0	Over heavy staining/leakage area
14	WB	P29	Cap	East	4.3 from left	3.7 from top	4.0	5	N	N		No bar			0.243		0.062			0.044			1 1/2	Over heavy staining/leakage area
15	WB	P29	Cap	East	4.8 from left	4.1 from top	4.0	5 1/2	N	N	1 3/4	#9	Light Corrosion										1/4	Over heavy staining/leakage area/Used for petrographic exam
16	WB	P29	Cap	South End	1.6 from left	1.3 from top	2.0	3 7/8	N	N		No bar											1.0	Over active leakage area
17	WB	P29	PS Girder (Far south)	South	0.4 from left	1.0 from bottom	2.0	5 1/4	N	N		No bar		0.152			0.026					< 0.008	1.0	Over active leakage area
18	WB	P29	PS Girder (Far south)	South	1.0 from left	1.0 from bottom	2.0	5 3/8	N	N		No bar		0.191			< 0.008					< 0.008	0	
19	WB	P29	PS Girder (Far south)	South	1.9 from left	0.8 from bottom	2.0	1 3/4	N	N	1 1/2	#4	Good				< 0.008						1/2	Next to active leakage area
20	WB	P29	Cap	South End	1.3 from left	1.2 from top	2.0	4.0	N	N		No bar											1 3/4	
21	WB	P29	PS Girder (Far south)	South	mid span	middle of web	2.0	2.0	N	N		No bar		0.010		< 0.008		< 0.008					1.0	Dried area
22	EB	P24	Cap	East	0.6 from left	0.4 from top	2.0	5.0 in 2 pcs	N	N	1 3/4	#8	Good	0.031		0.010						< 0.008	1 1/4	Over dry stained area
23	EB	P24	Cap	East	4.8 from left	3.0 from top	2.0	2 3/4	N	N	2 3/8	#8	Light corrosion										1.0	Over dry stained area
24	EB	P24	Cap	East	11.9 from left	0.4 from top	2.0	2 3/4	N	N		No bar											1 1/4	Over dry stained area

* EB: Eastbound, WB: Westbound

Table 3. Summary of Field Core Data

Core ID	Coring Location						Core Dimension		Condition of Coring Location		Extracted Rebar			Acid-soluble chloride content (wt. % by sample weight)										Max. Depth of Carbonation (in.)	Note
	Bound	Bent No.	Component	Face	x (ft.)	y (ft.)	Diameter (in.)	Length (in.)	Delamination @ depth	Crack (width, mils)	Cover (in.)	Size	Condition	0-1/8 in.	1/8-3/8 in.	1.0-11/8 in.	11/4-11/2 in.	11/2-15/8 in.	2.0-21/8 in.	21/2-23/4 in.	3.0 -31/8 in.	4.0 -41/8 in.			
25	EB	P24	South Column	East	0.7 from left	5.5 from bottom	2.0	2 1/4	N	N	2 1/8	#3	Good										5/8	
26	EB	P24	South Column	East	0.6 from left	2.4 from bottom	2.0	5 1/2	N	N	No bar												1.0	Over dry area
27	EB	P24	Cap	South End	1.6 from left	1.3 from top	2.0	3 7/8 in 2 pcs	N	Y	No bar			0.039		0.023					0.023		1 3/4	
28	EB	P24	PS Girder (Far south)	South	0.4 from left	1.0 from bottom	2.0	5 1/2	N	N	No bar												0.2	Used for petrographic exam
29	EB	P9	South Column	West	0.8 from left	2.0 from bottom	2.0	4.5	N	N	No bar			0.584		0.096						0.008	1 1/8	
30	EB	P9	South Column	South	0.8 from left	5.5 from bottom	2.0	5 1/4	N	N	No bar												3/4	Over dark stained area
31	WB	P8	North Column	South	0.9 from left	2.0 from bottom	2.0	5 1/2 in 2 pcs	N	N	No bar			0.040		< 0.008						< 0.008	7/8	Over dark stained area
32	WB	P8	North Column	South	1.0 from left	5.5 from bottom	2.0	3 1/4	Y @ #3	Horizontal crack @ #3	1.5 for #3 2.0 for #10	#3 & #10	Good										1 1/2	Over dark stained area

* EB: Eastbound, WB: Westbound

Figure 1. Overview of U1020 Overpass at Billings, MT.

Figure 2. Half-cell potential measurement on the eastbound deck span 5.

Figure 3. Instantaneous corrosion rate measurement on a column using a Gecor 6 device.

Figure 4. The eastbound Bent No. 27 cap showing a spall and delamination.

Figure 5. Actively leaking westbound Bent No. 29 (east face).

Figure 6. Close-up of the leaking joint shown in Figure 5.

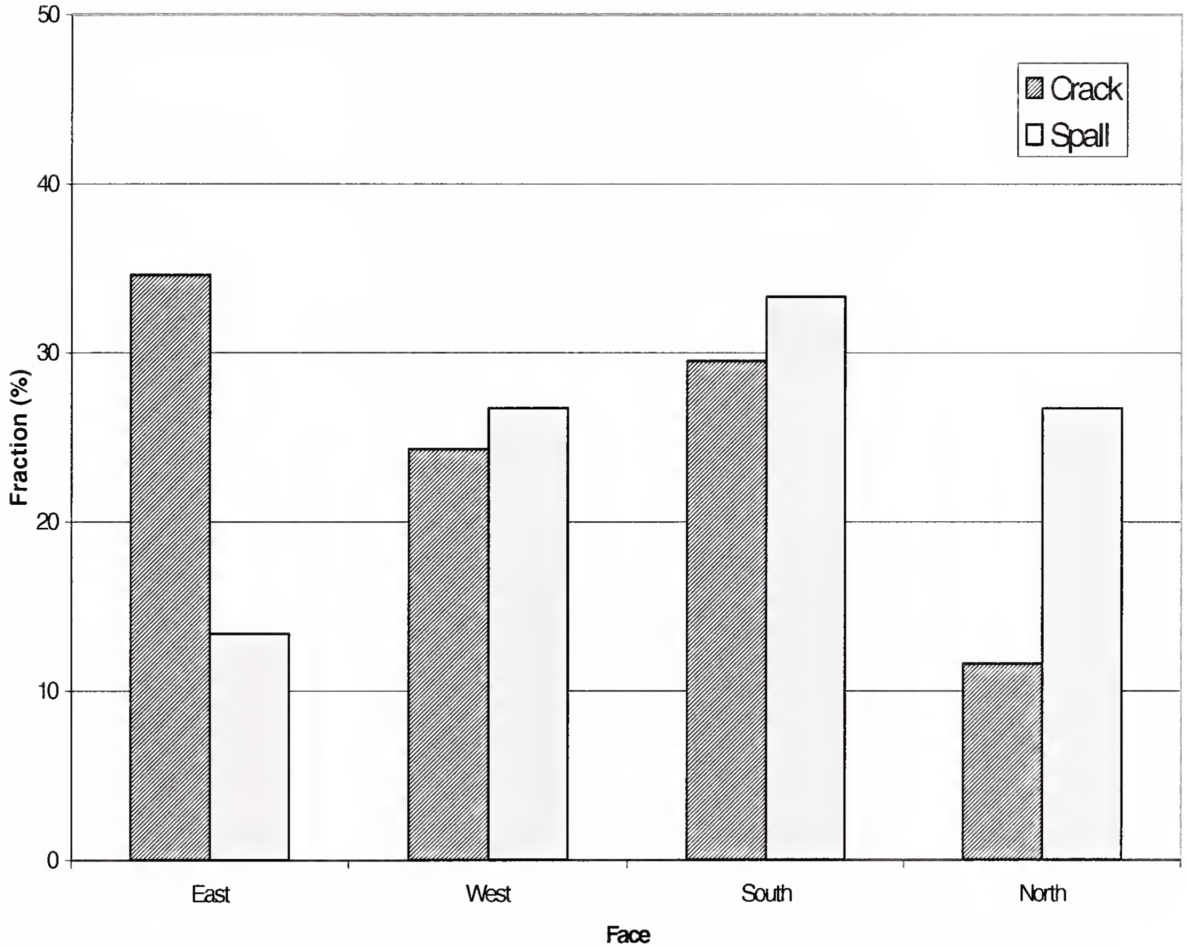


Figure 7. Comparison of Damage Frequency Per Column Exposure Face.

Figure 8. A drainage pipe and a wetted cap and column.

Figure 9. Deteriorated eastbound south column of Bent No. 27.

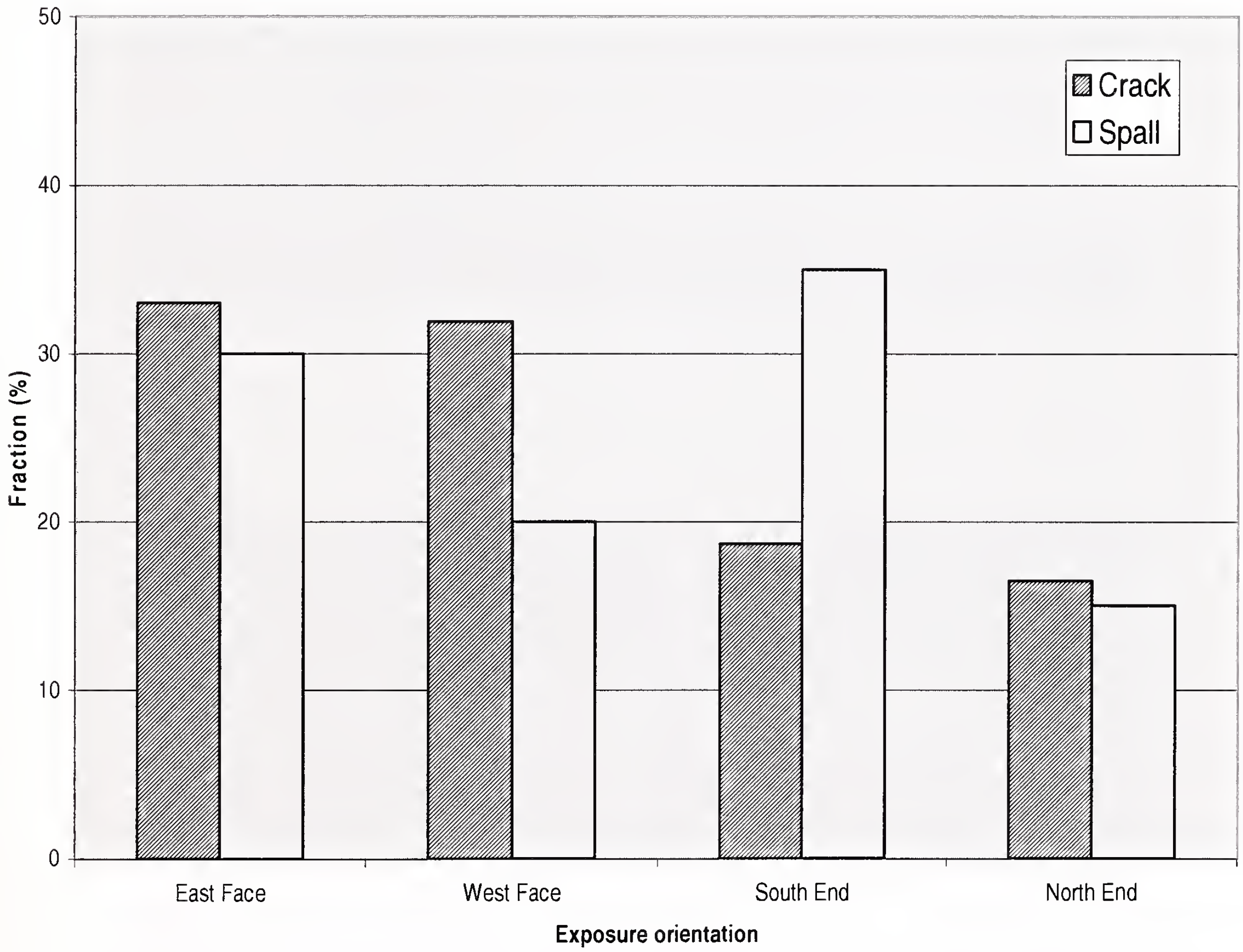


Figure 10. Comparison of Damage Frequency Per Bent Cap Face.

Figure 11. Prestressed beam No. 5 on Bent No. 25 of the eastbound bridge.

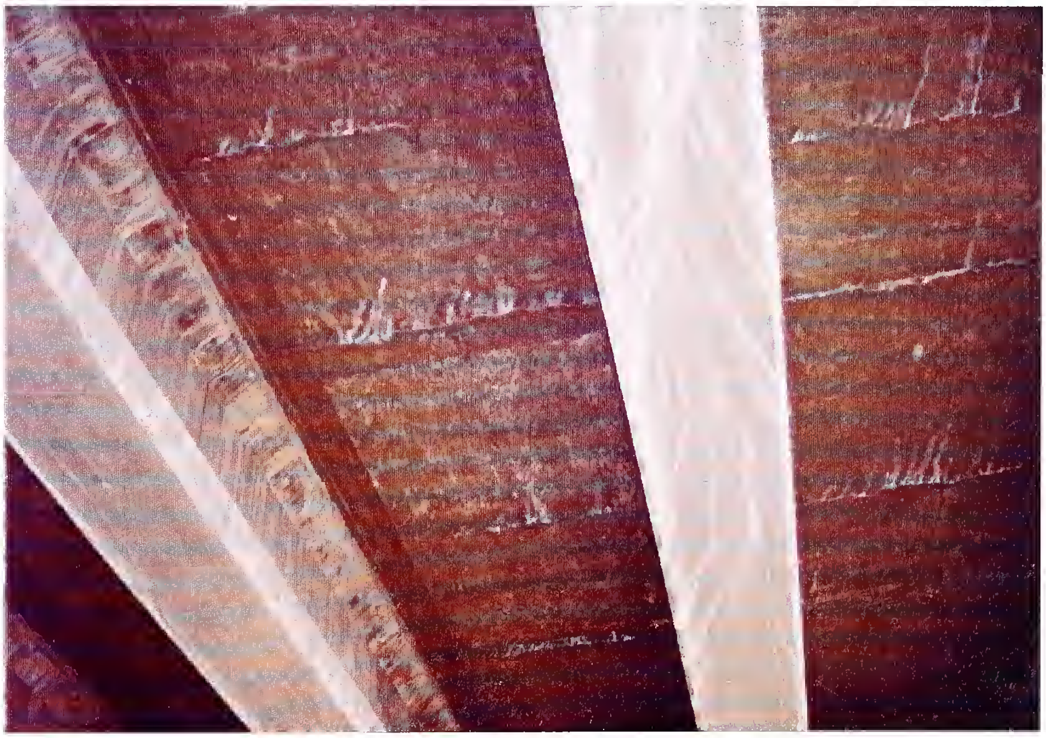


Figure 12. Typical condition of underside cracks.

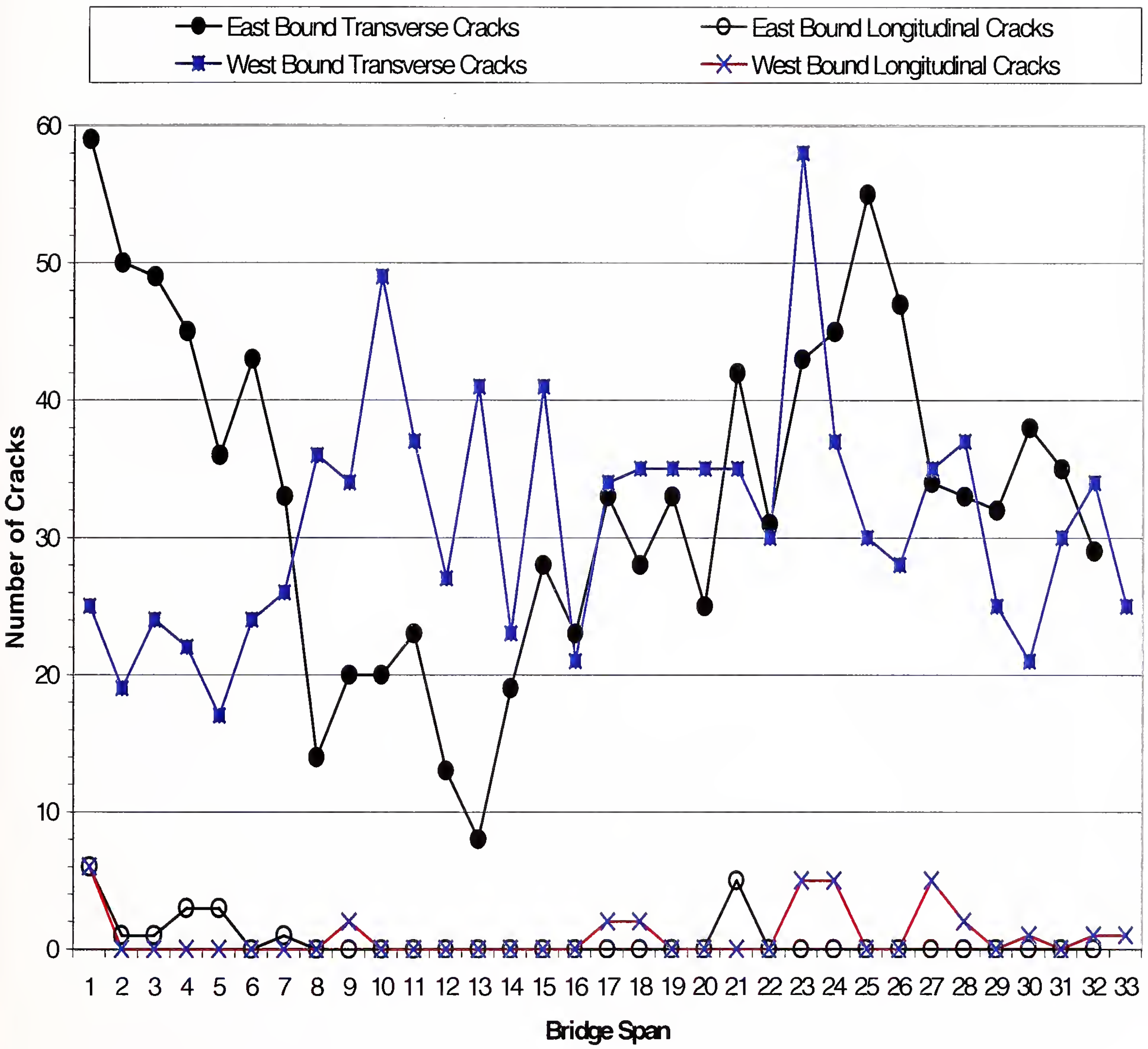


Figure 13. Variation of underside cracks along the bridge length.

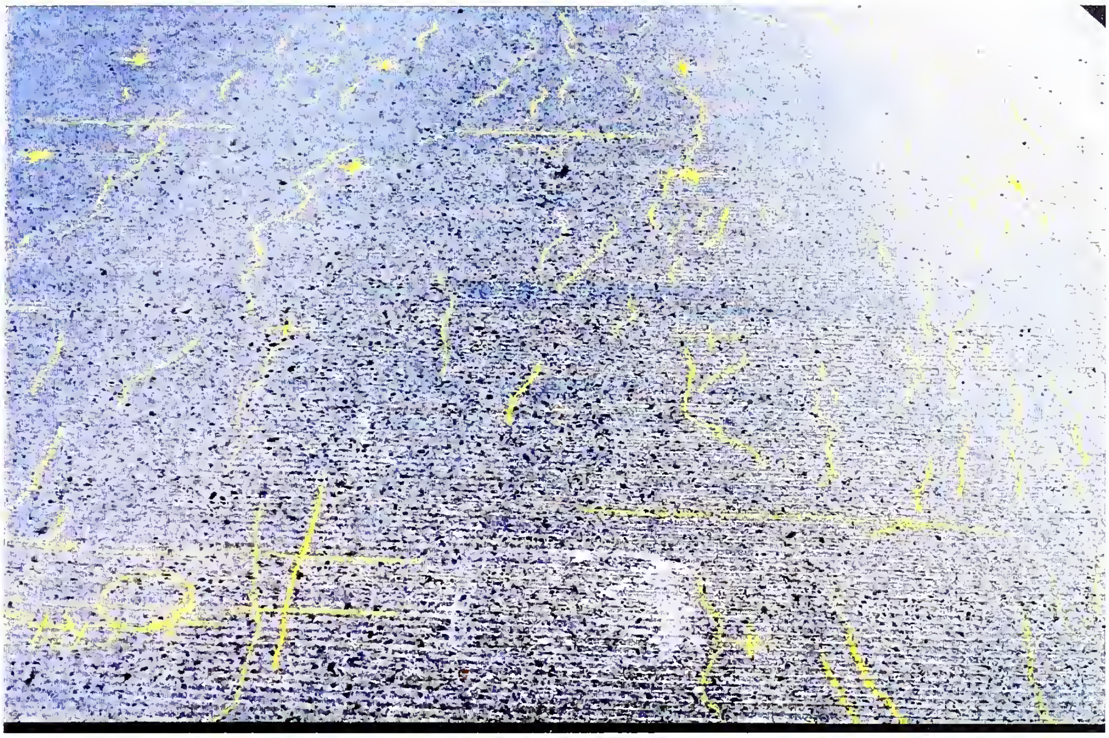


Figure 14. Condition of deck span 5 showing many cracks.

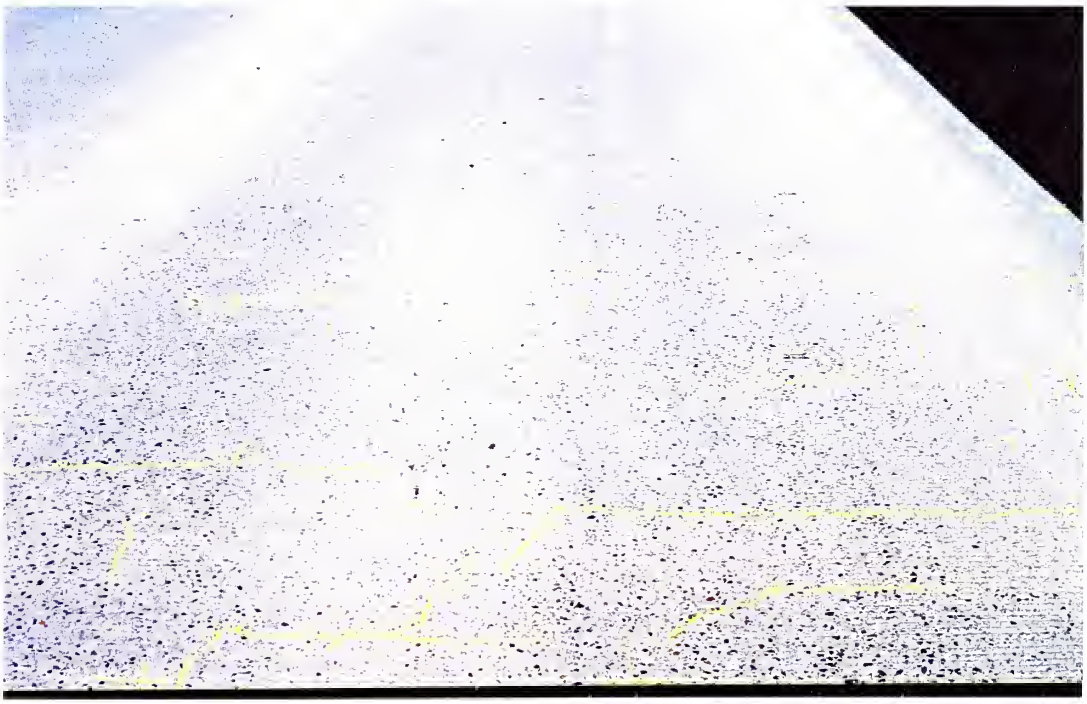


Figure 15. Similar condition shown in deck span 25.

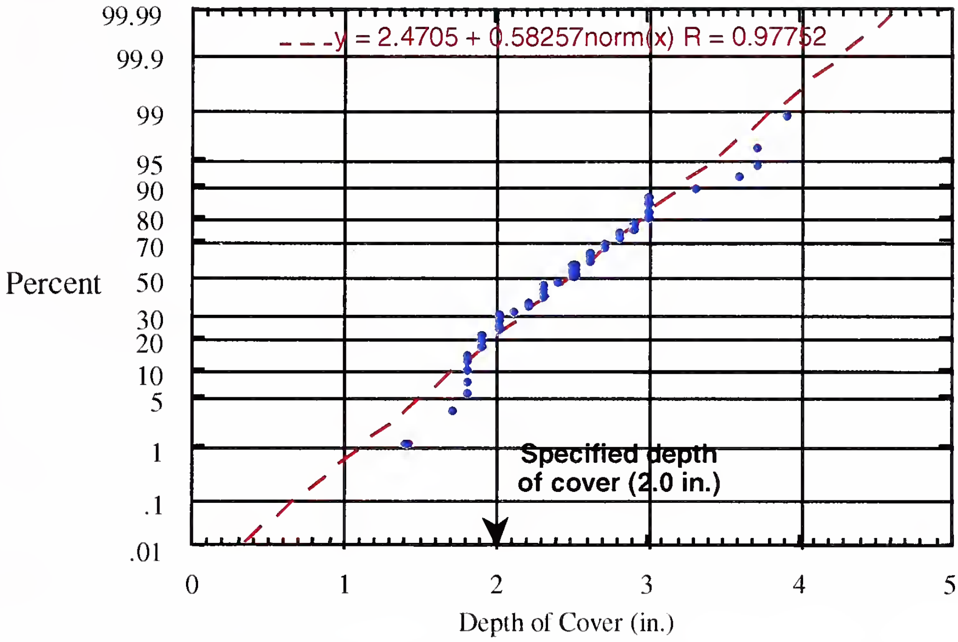


Figure 16. Cumulative distribution of depth of cover data for bent caps.

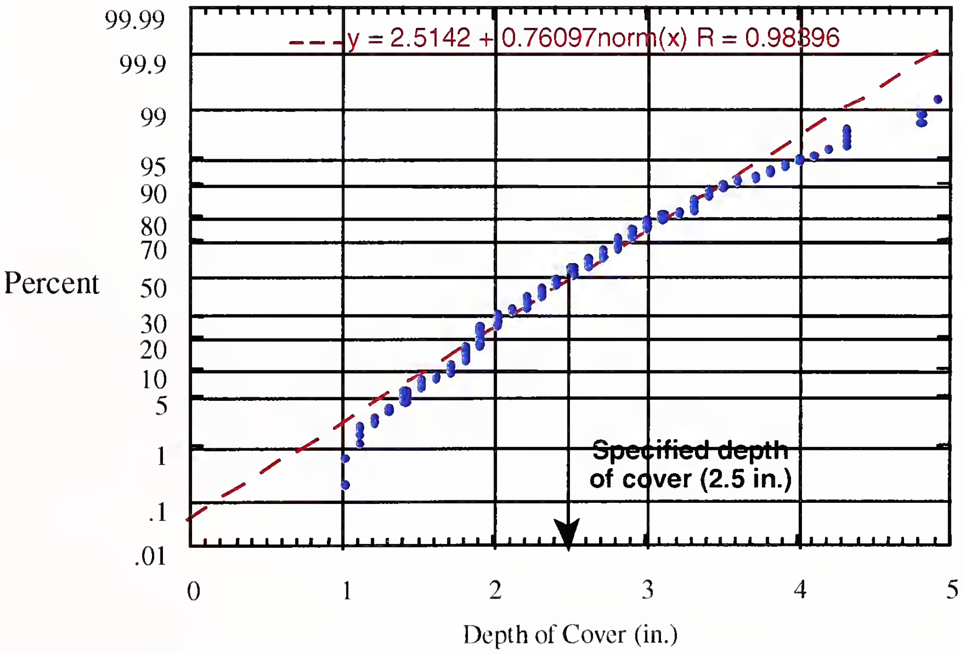
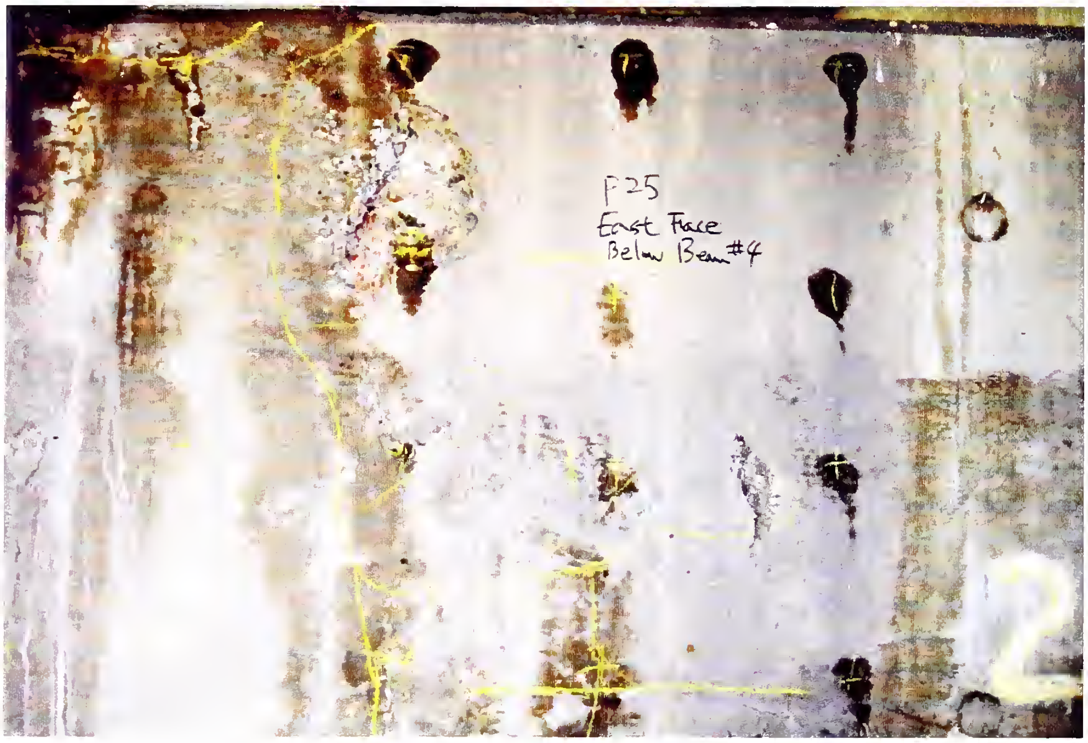
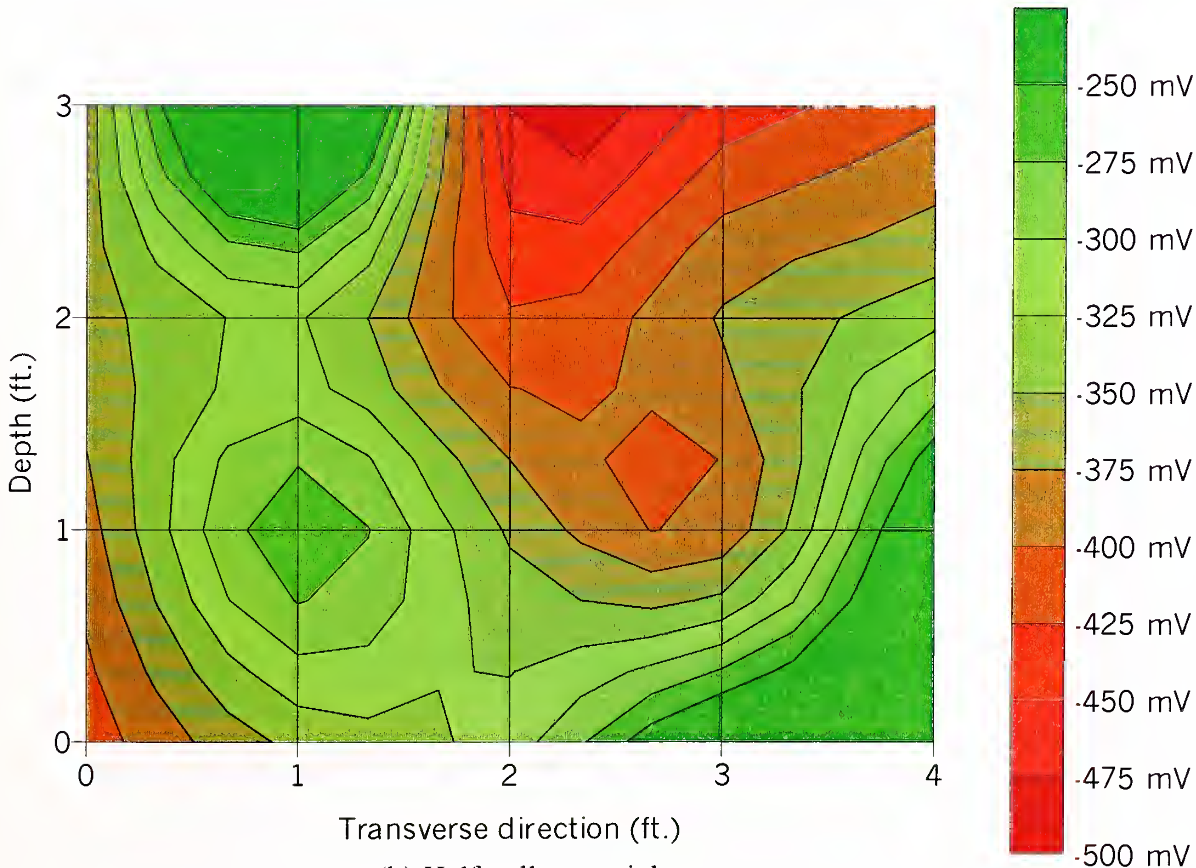


Figure 17. Cumulative distribution of depth of cover data for columns.

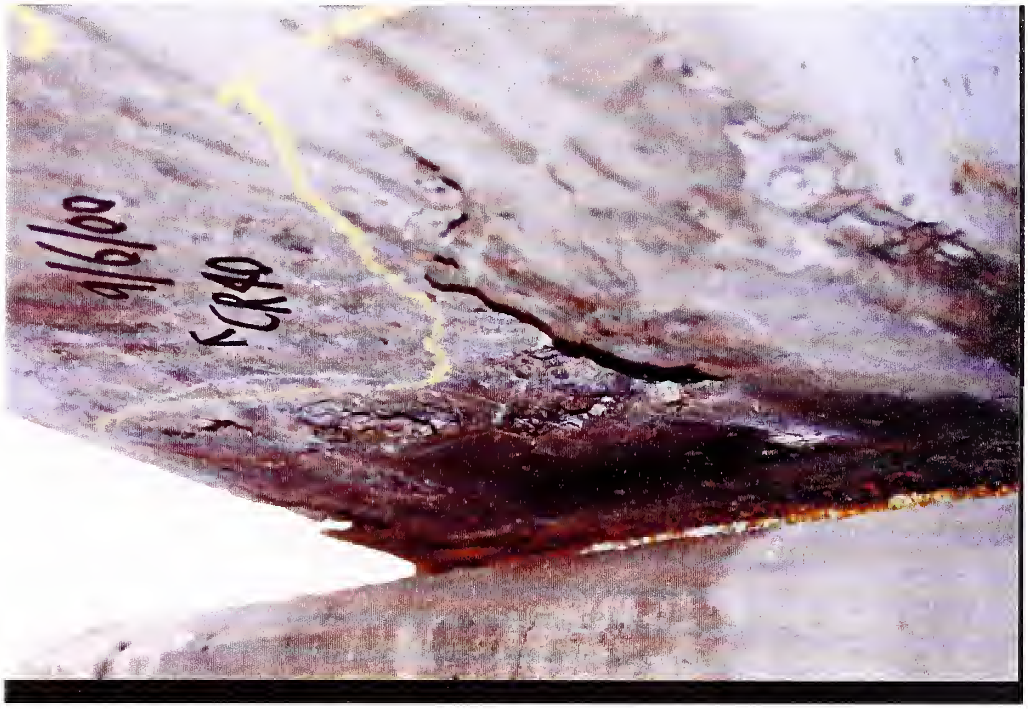


(a) Photograph

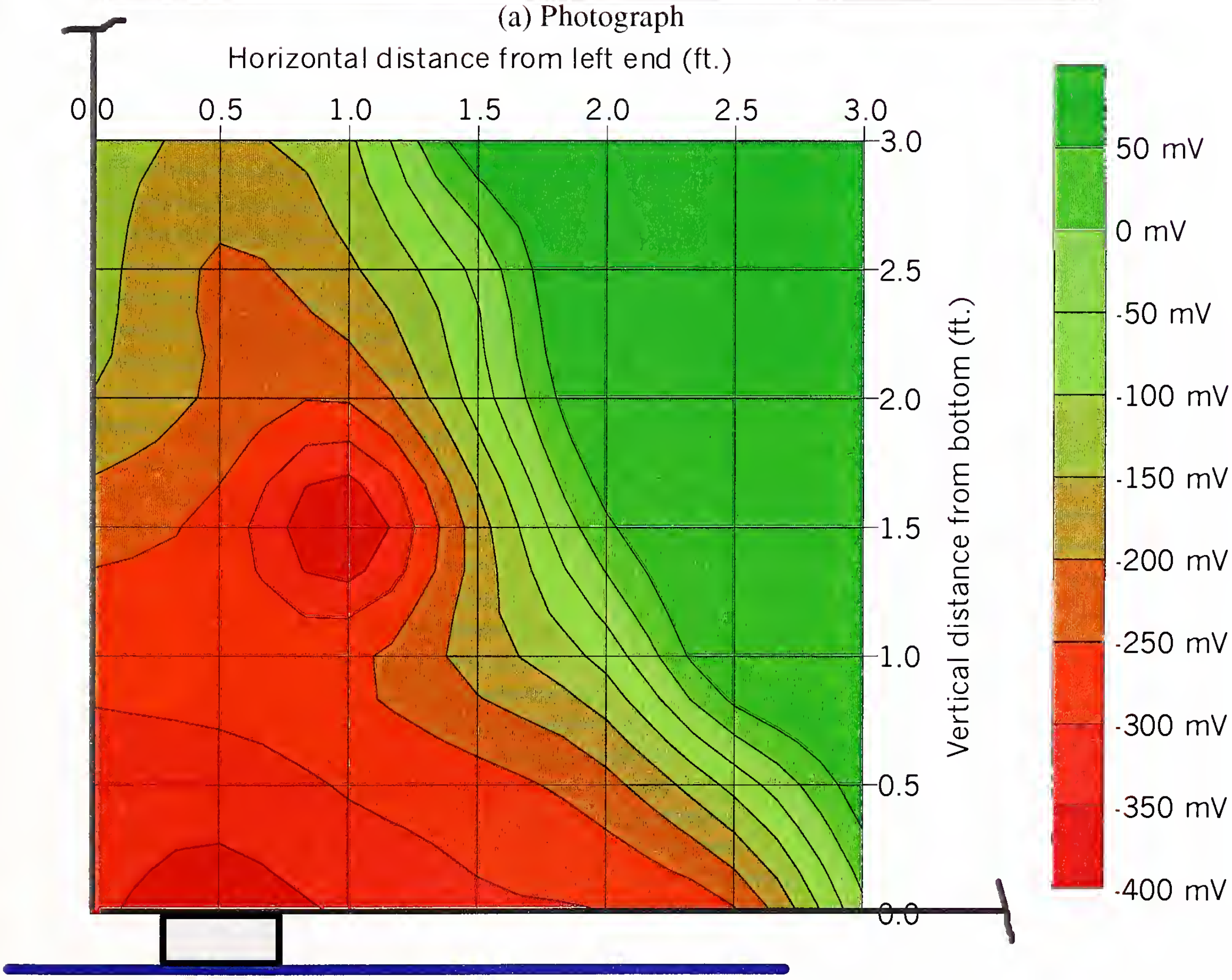


(b) Half-cell potential contour map

Figure 18. Half-cell potential mapping of east cap face of eastbound Bent No. 25.



(a) Photograph

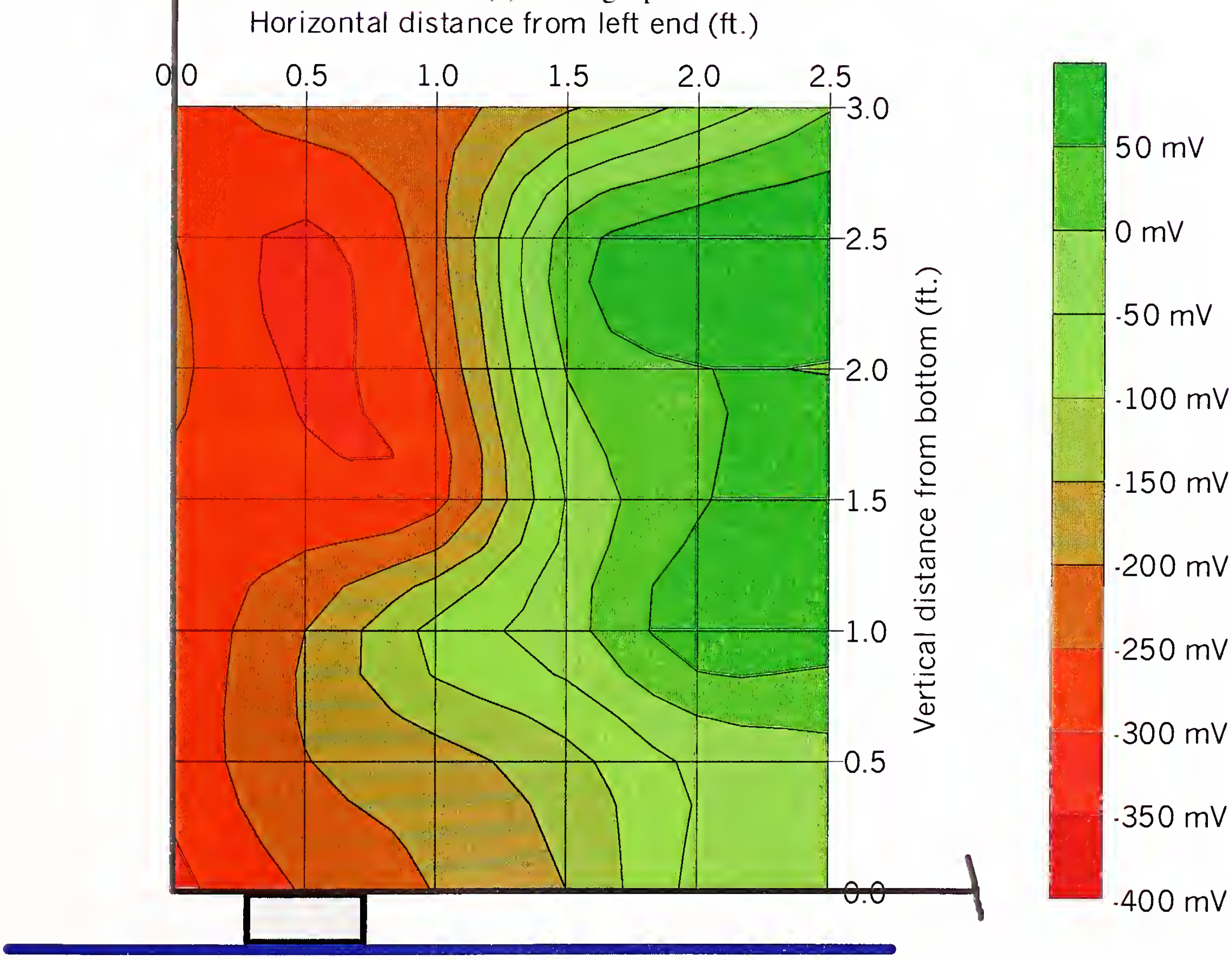


East Bound Bent No. 25

(b) Half-cell potential contour map

Figure 19. Half-cell potential mapping of a prestressed beam of Bent No. 25.

(a) Photograph



West Bound Bent No. 29

(b) Half-cell potential contour map

Figure 20. Half-cell potential mapping of a prestressed beam of Bent No. 29.

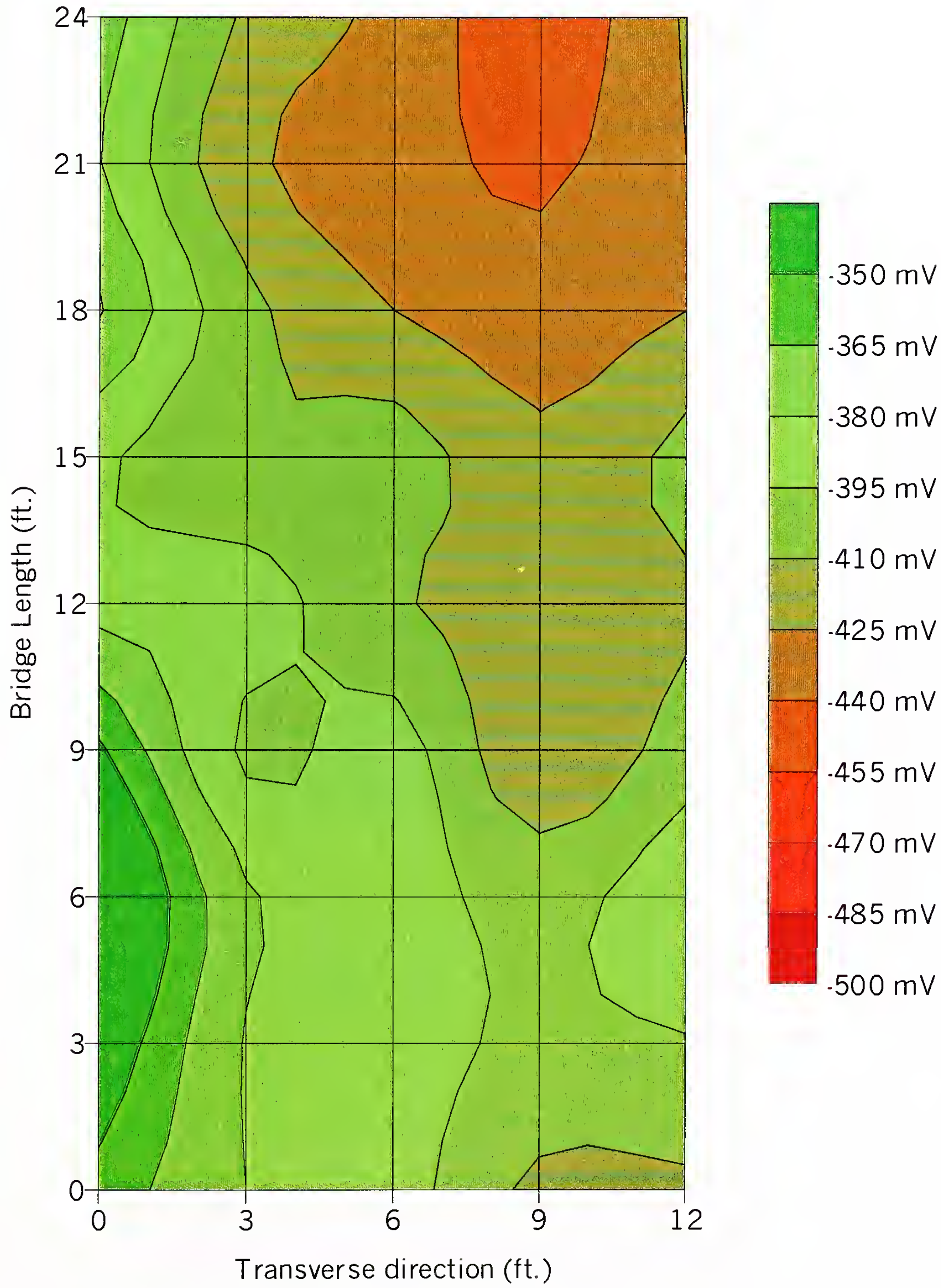


Figure 21. Half-cell potential contour map of deck span 5.

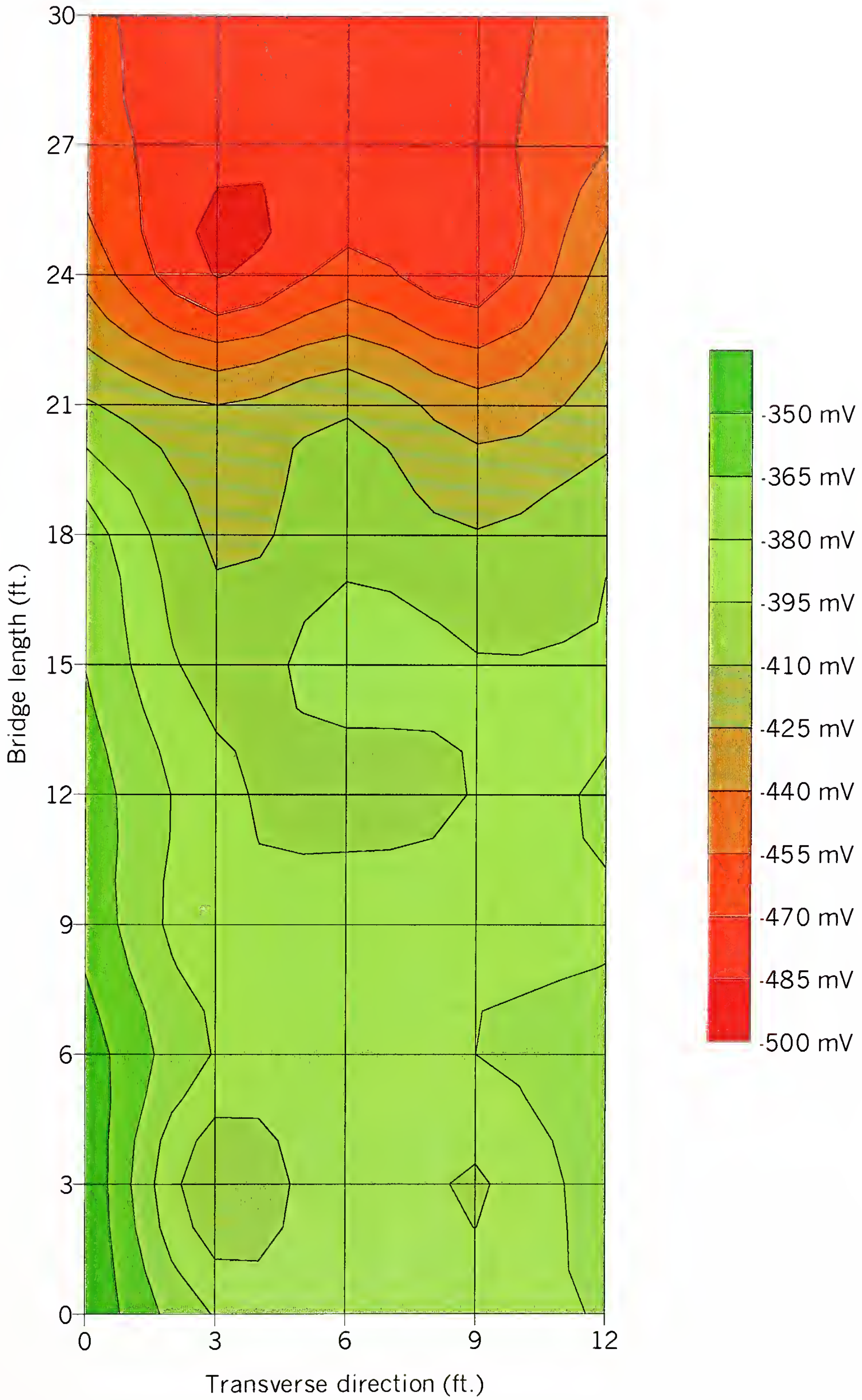


Figure 22. Half-cell potential contour map of deck span 5.

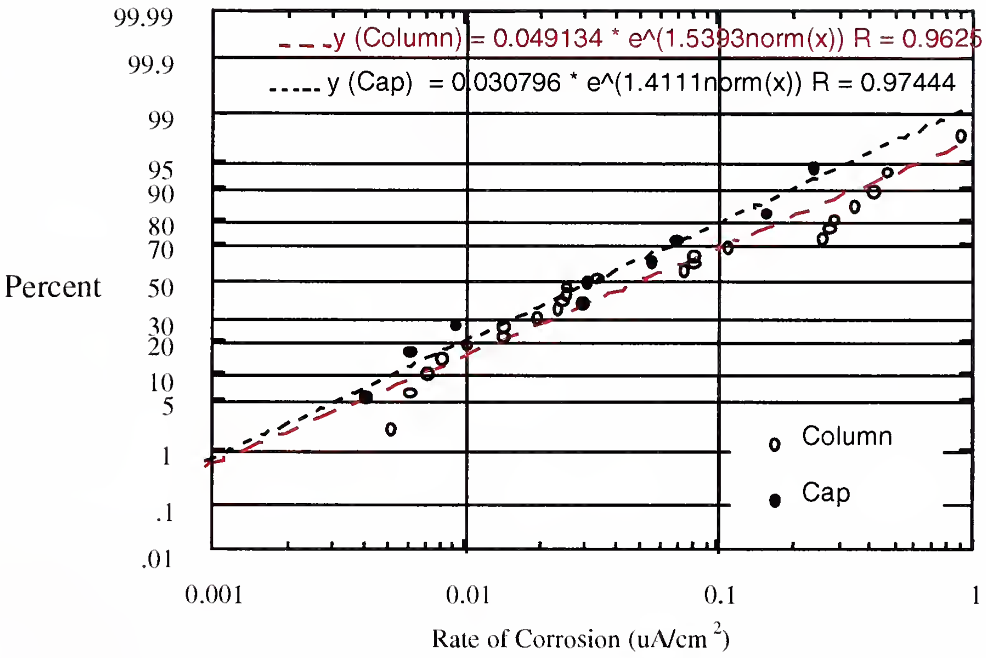


Figure 23. Cumulative distribution of corrosion rates taken from columns and caps.

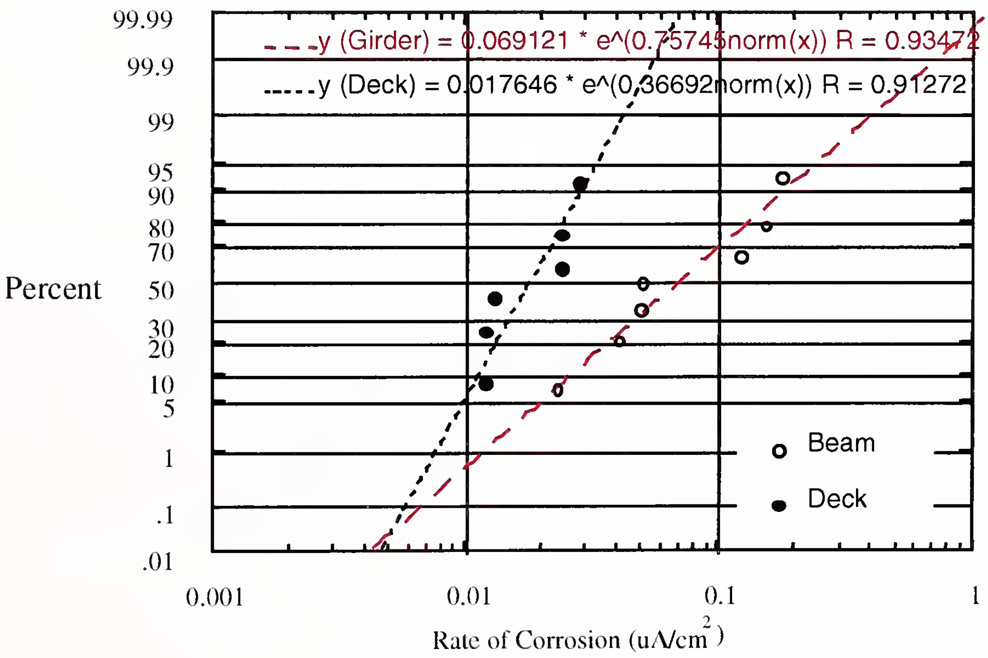
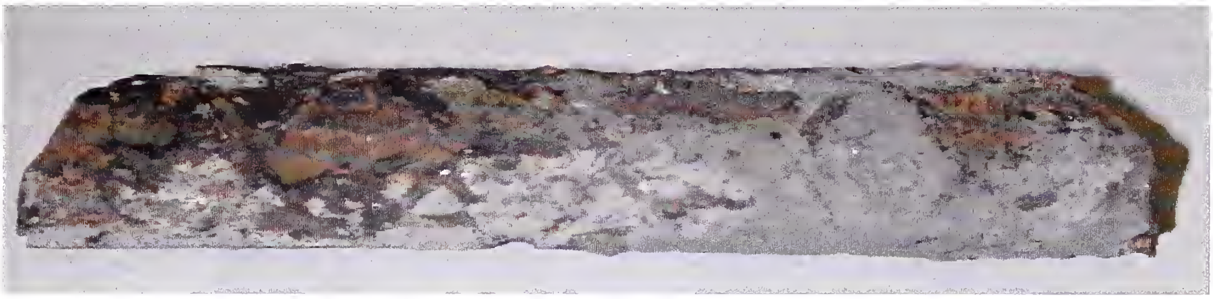
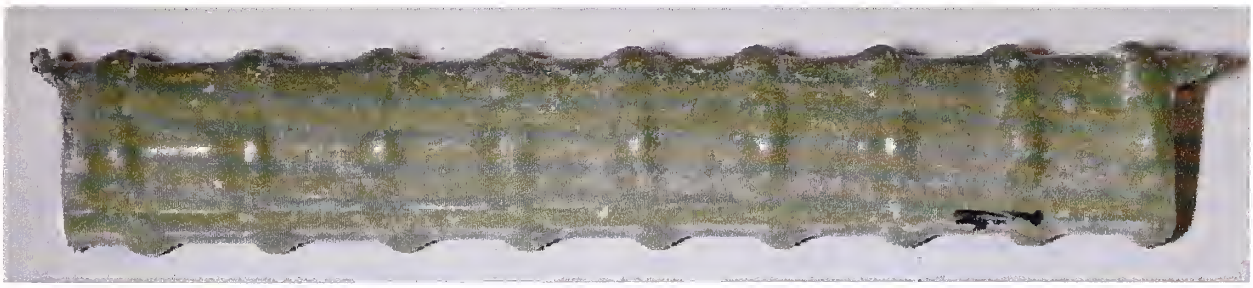


Figure 24. Cumulative distribution of corrosion rates taken from beams and decks.

(a) A #8 black reinforcing bar with mild corrosion (extracted from C23).



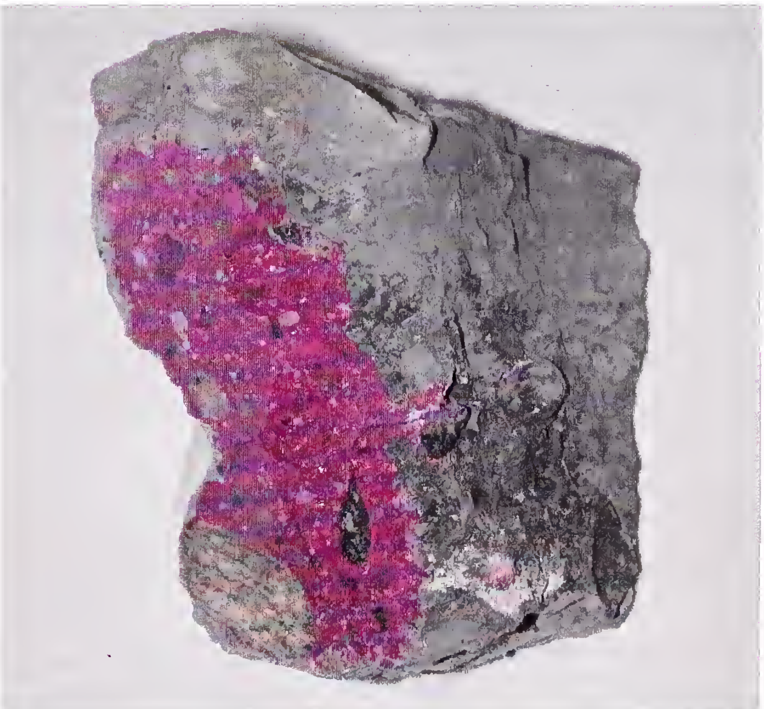
(b) A heavily corroded #5 black reinforcing bar (extracted from C12)



(c) A #5 epoxy-coated reinforcing bar in excellent condition (extracted from C3)

Figure 25. Typical conditions of extracted reinforcing bars.

(a) Carbonated Core #30



(b) Carbonated Core #7 taken from a cracked deck location

Figure 26. Two examples of carbonation testing.

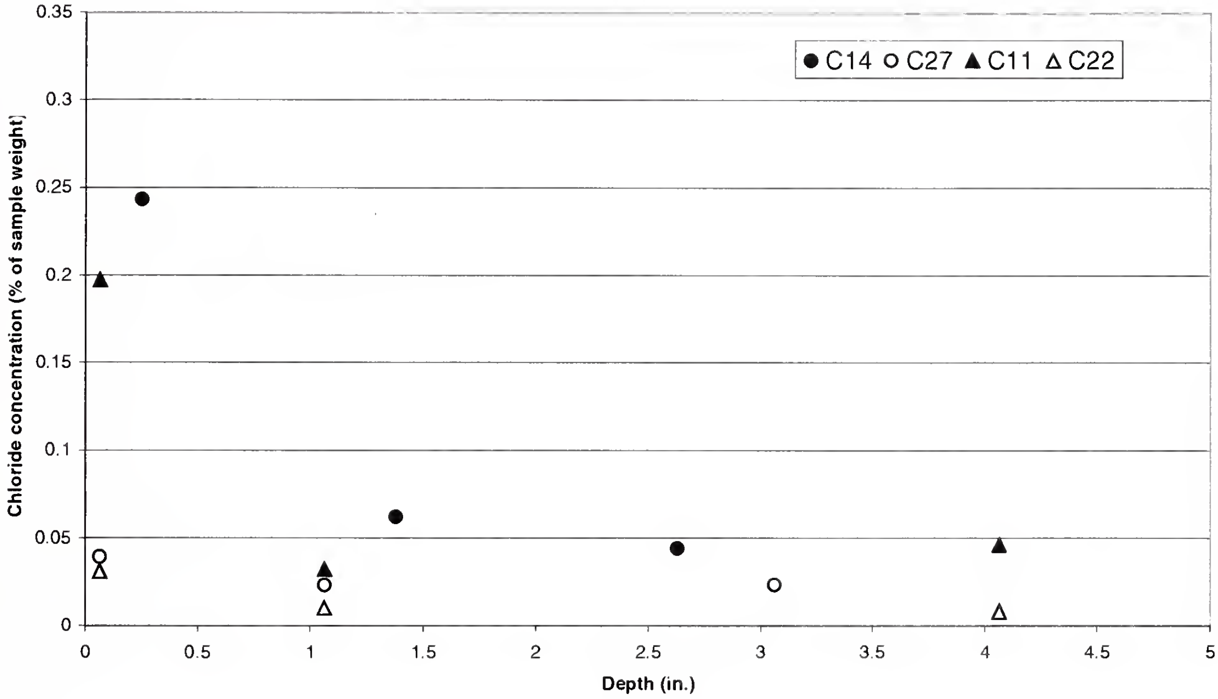


Figure 27. Chloride profiles of bent cap cores.

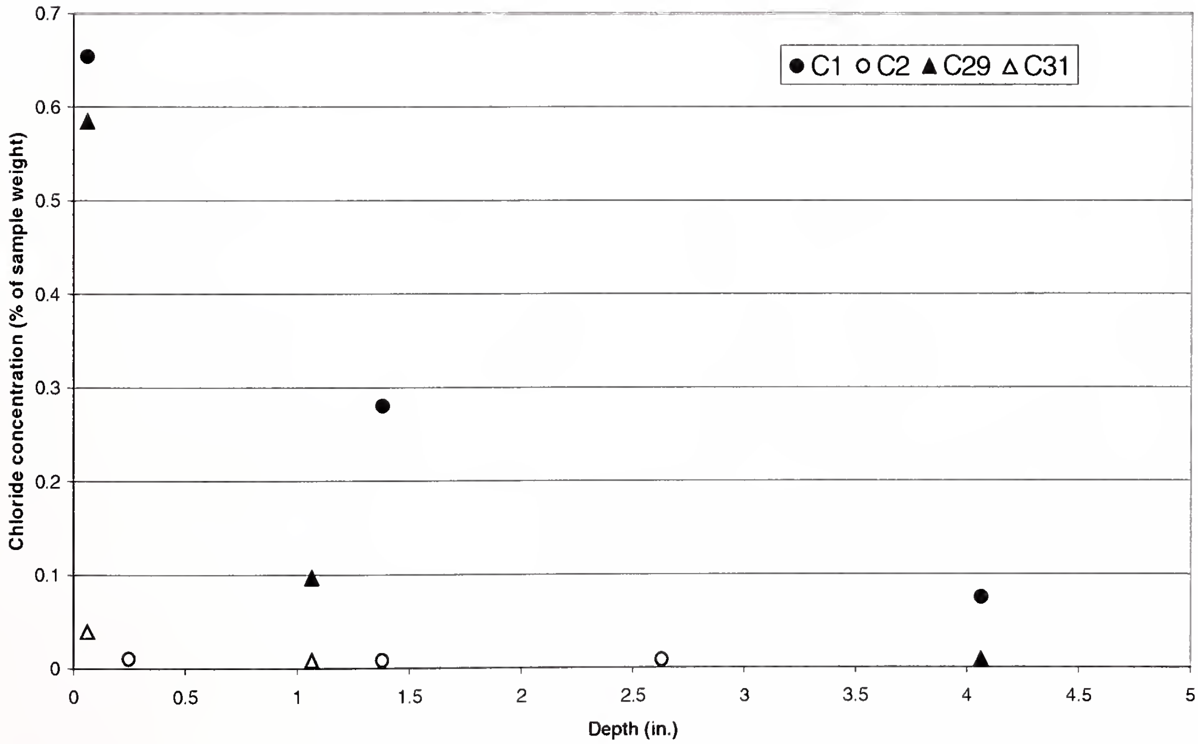


Figure 28. Chloride profiles of column cores.

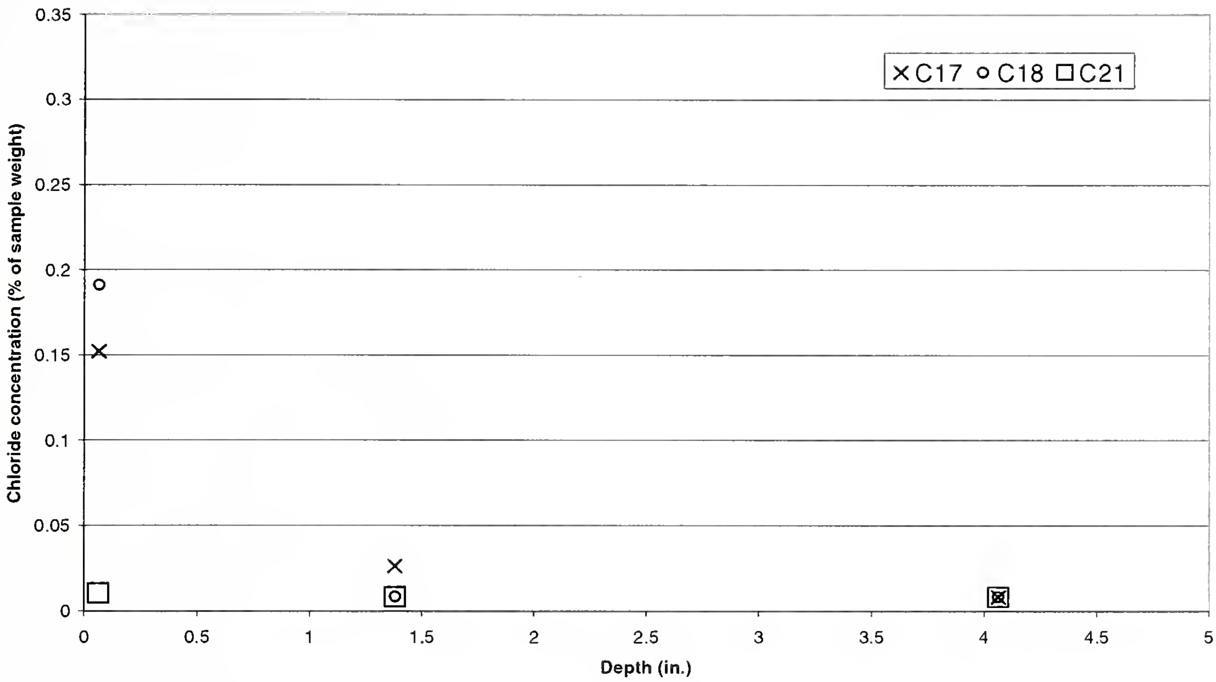


Figure 29. Chloride profiles of prestressed beam cores.

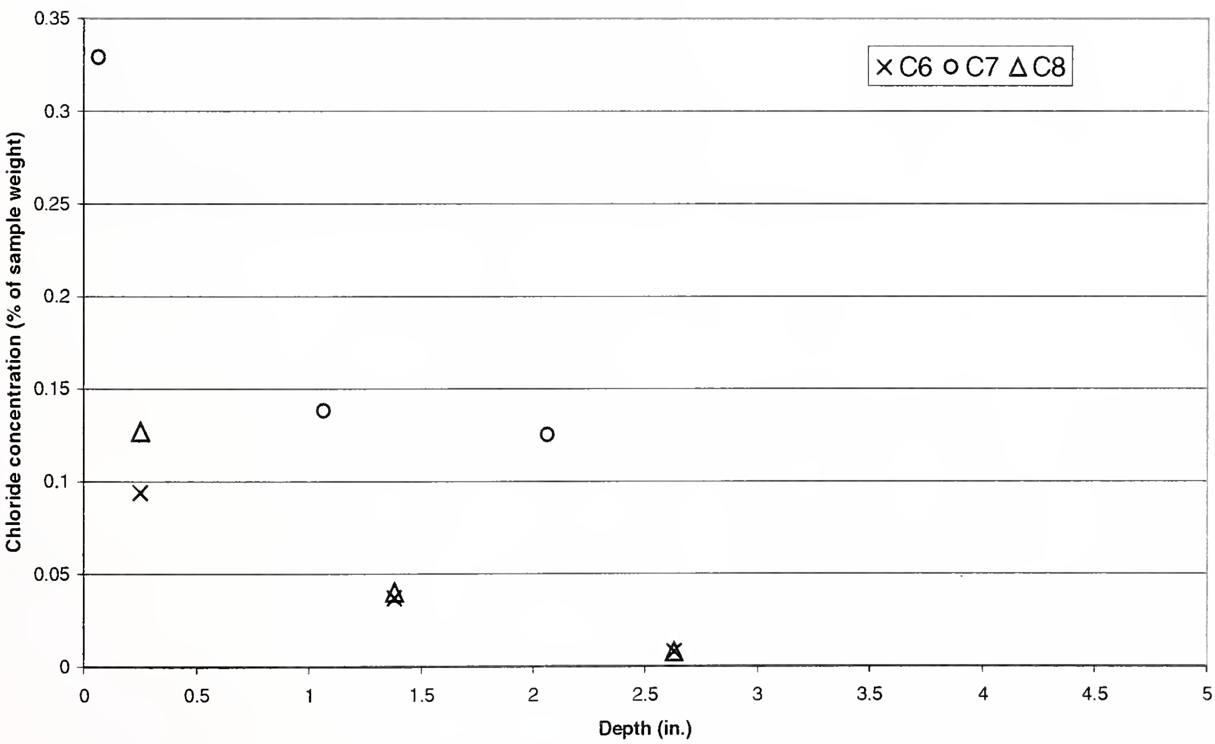


Figure 30. Chloride profiles of deck cores.

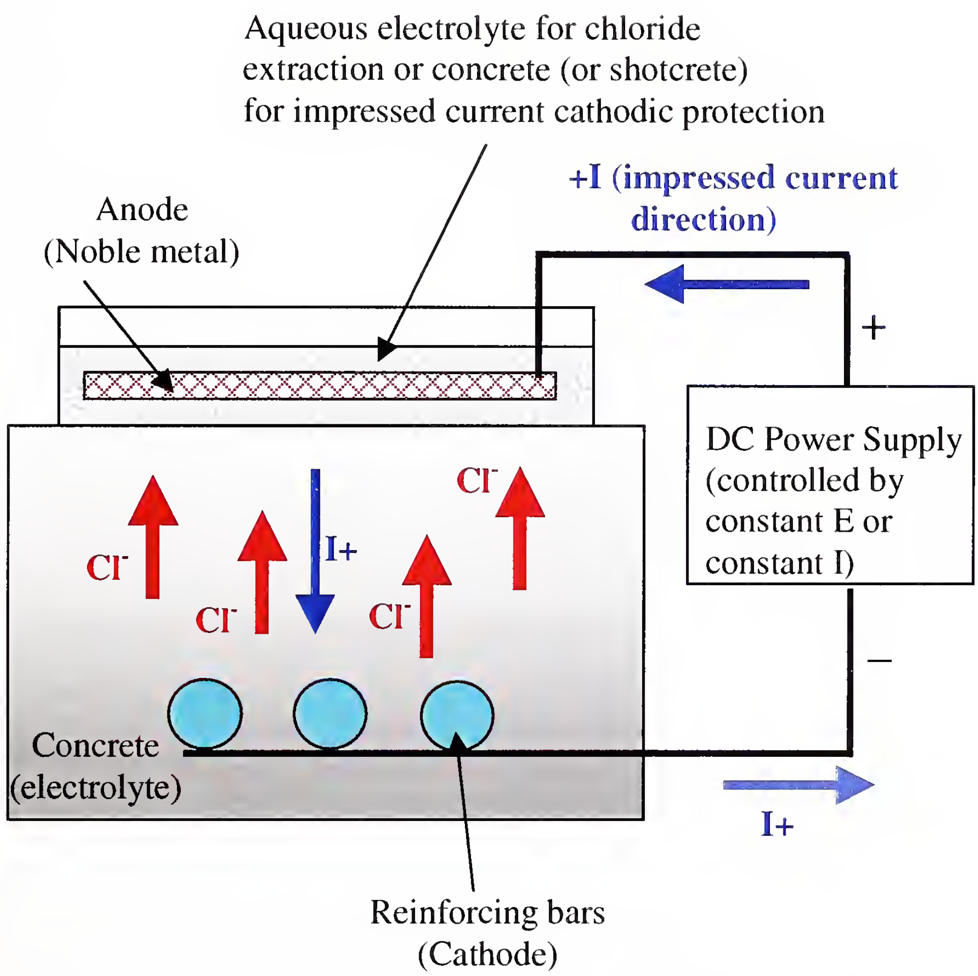
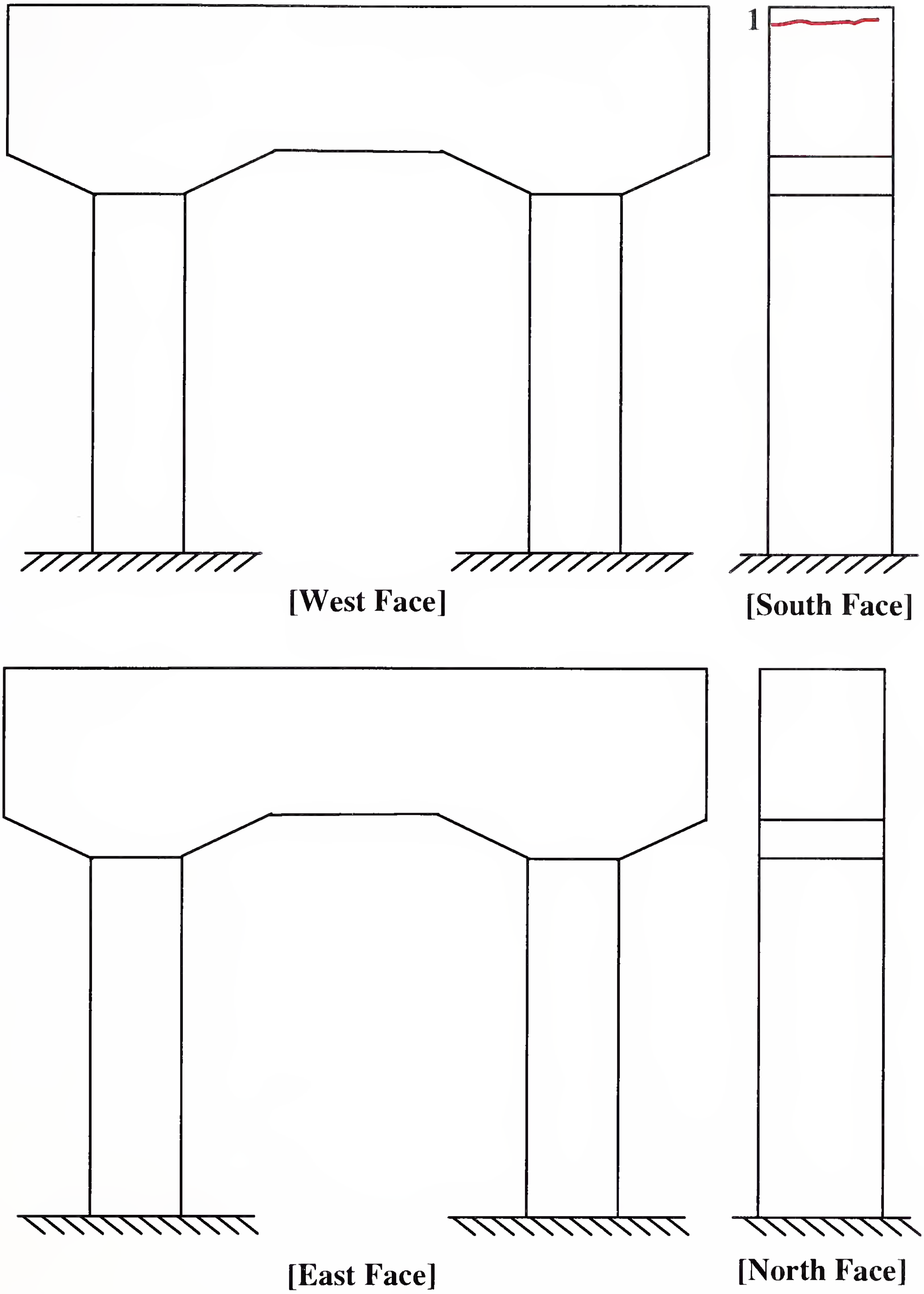


Figure 31. Principle of impressed current cathodic protection and electrochemical chloride extraction technique.

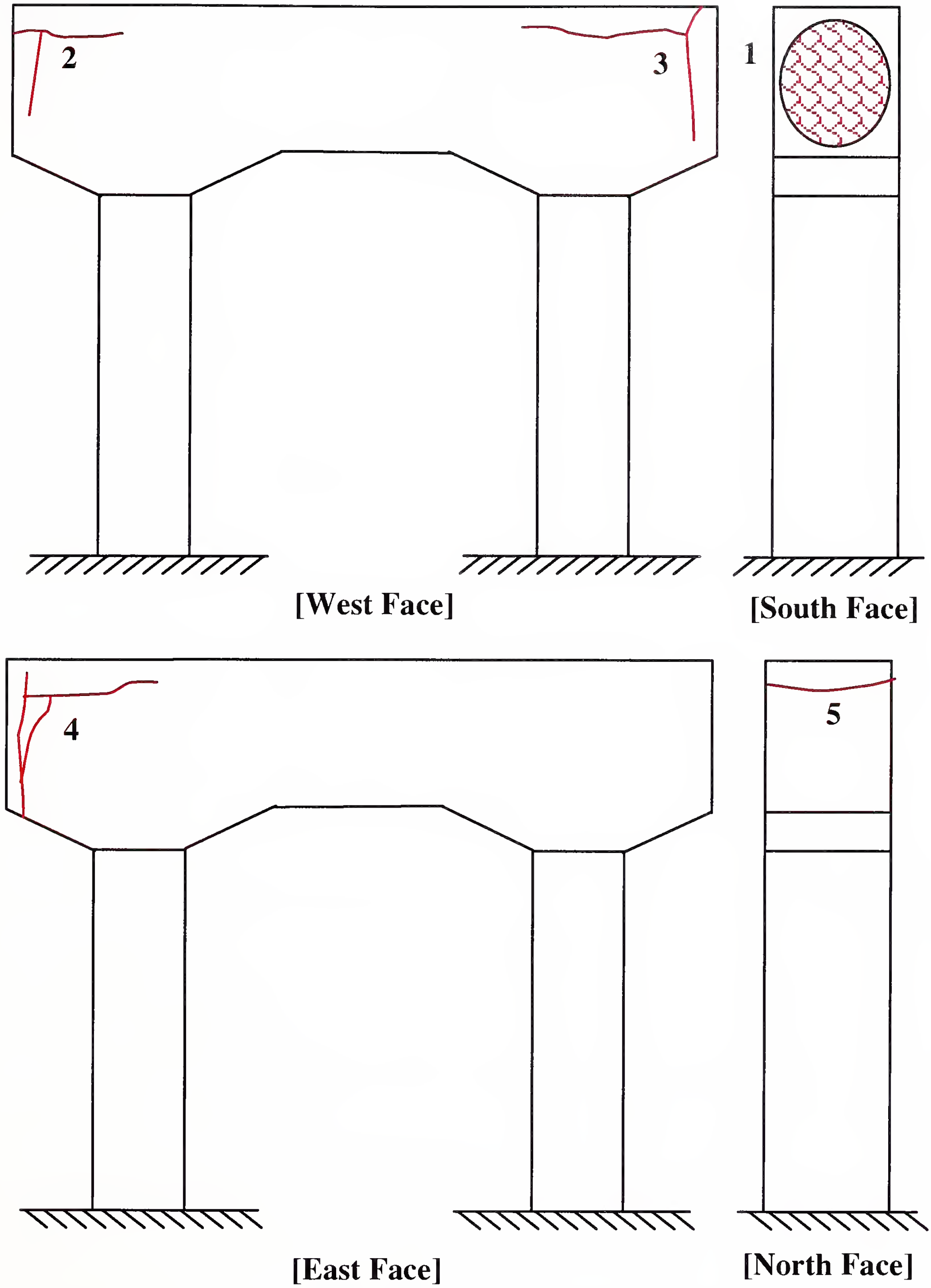
APPENDIX A

Condition Survey Data Sheets (Bents)



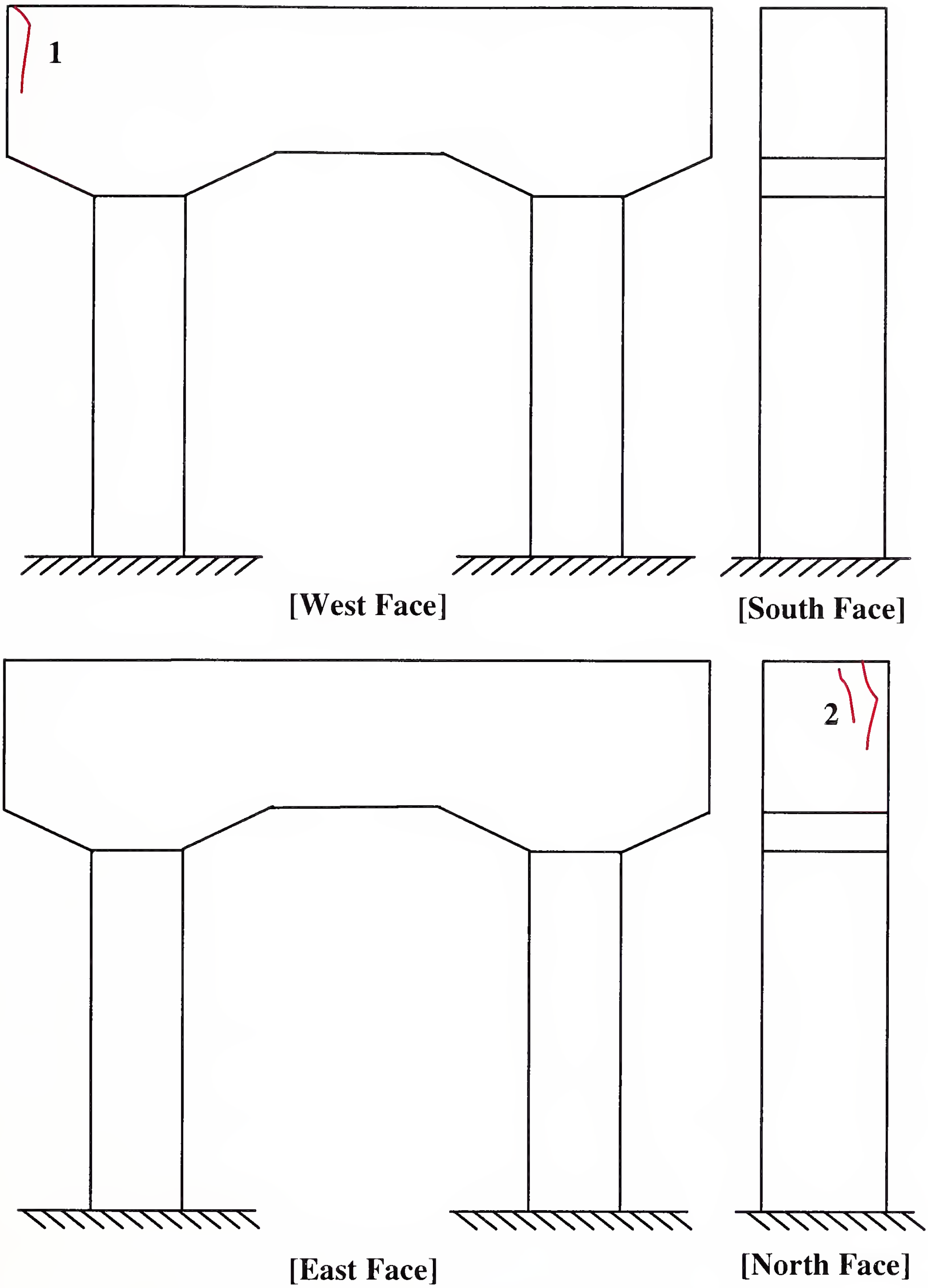
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage Test Performed: None
	Cap End	South	Crack (1)	

Figure 1A. Condition of Bent No. 2 (East Bound).



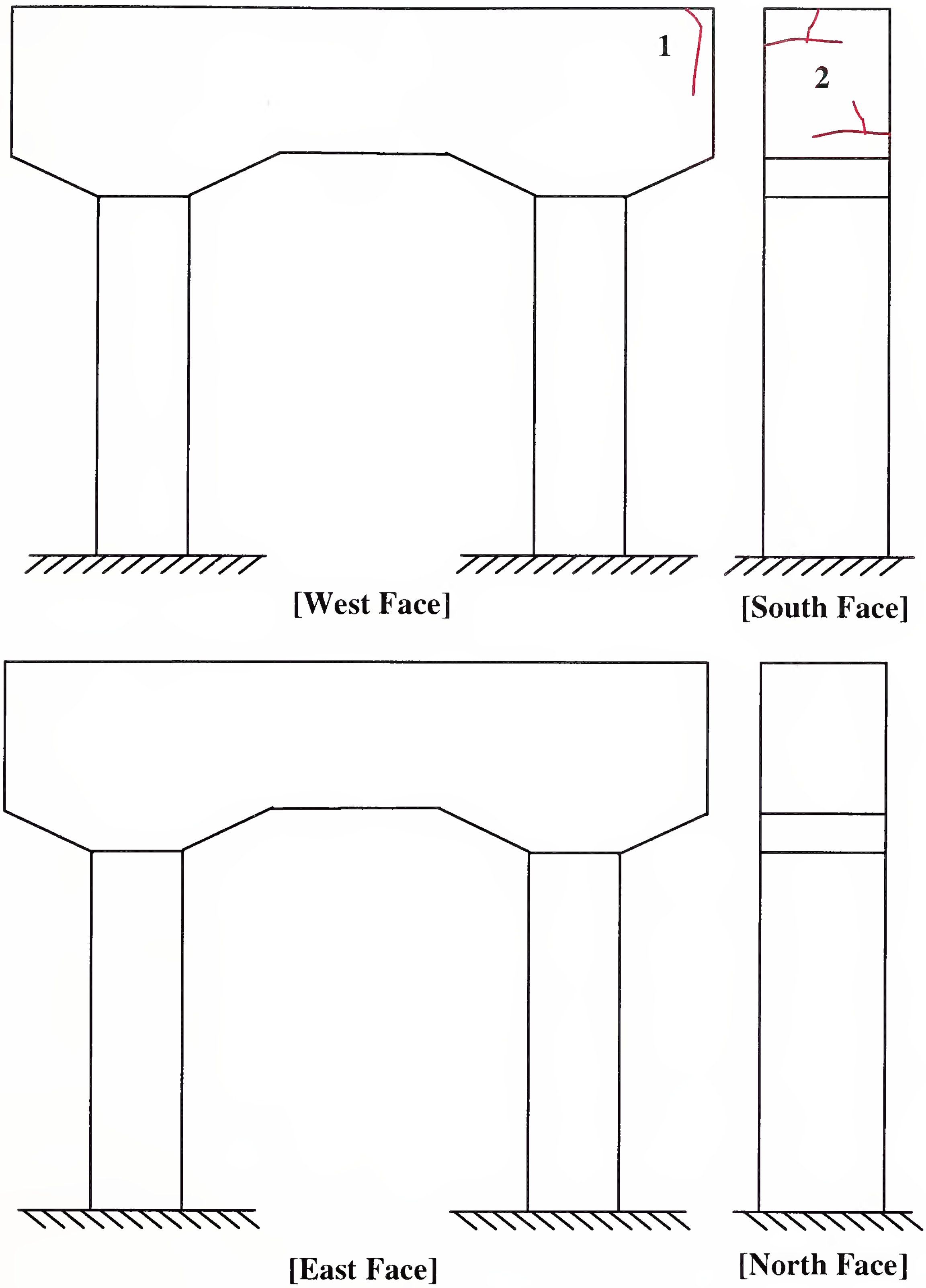
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but moist south end Test Performed: None
	Cap	South	Pattern cracking (1)	
	Cap	West	Two cracks (2)	
	Cap	West	Two cracks (3)	
	Cap	East	Multiple cracks (4)	
	Cap	North	A crack (5)	

Figure 2A. Condition of Bent No. 3 (East Bound).



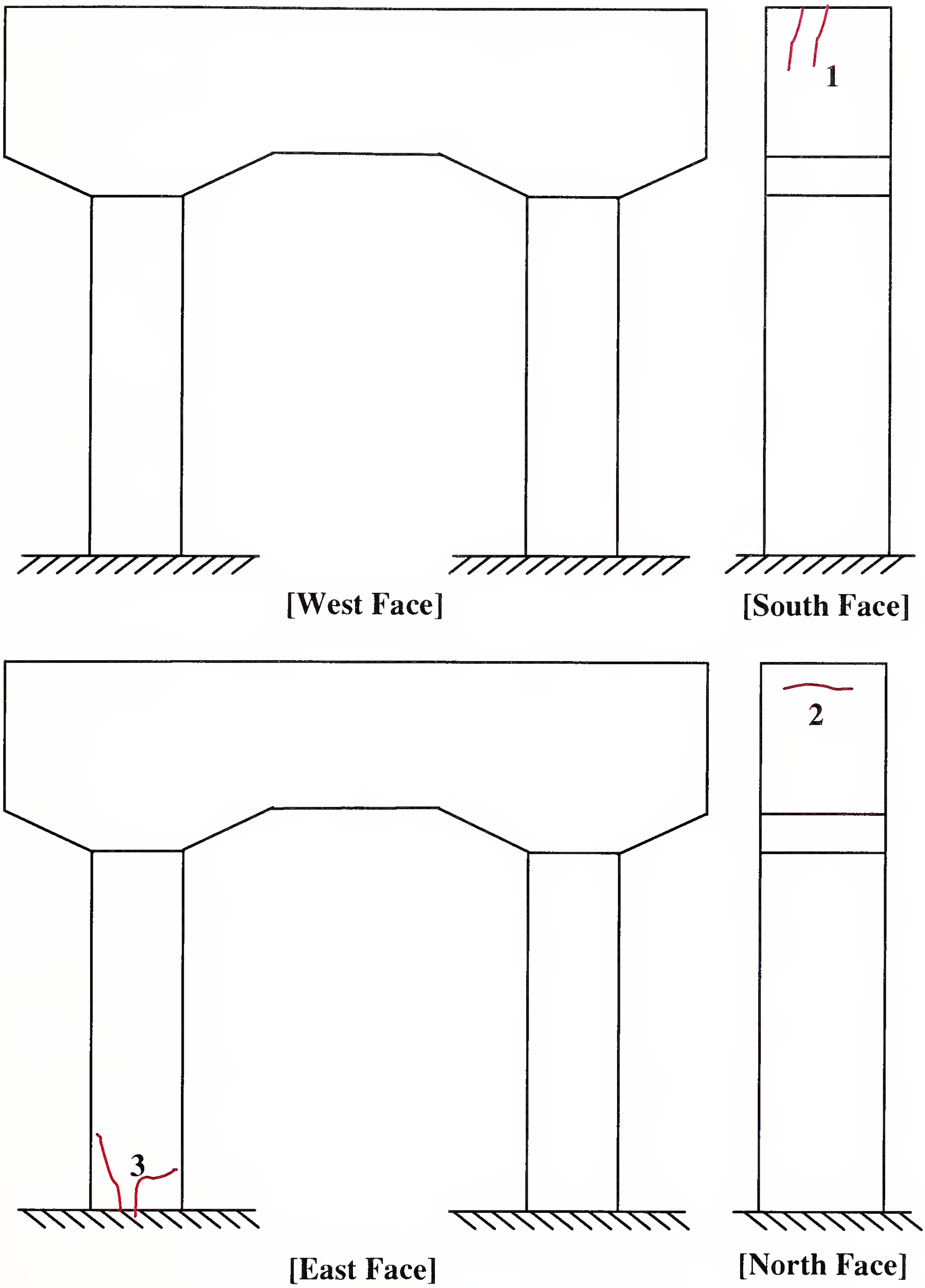
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage
	Cap	West	A crack (1)	
	Cap	North	Cracks (2)	
				Test Performed: None

Figure 3A. Condition of Bent No. 4 (East Bound).



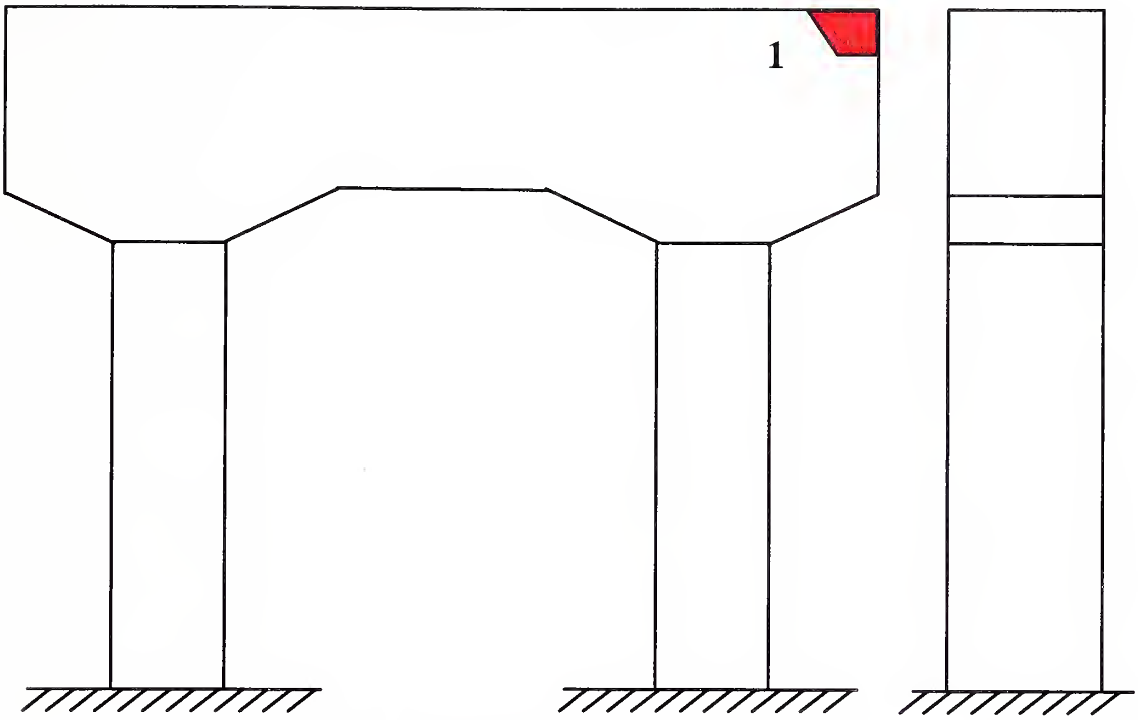
	Location	Face	Description of Damage (No.)	Leakage Condition: Leakage below beams 3-4, 4-5 Test Performed: None
Damage	Cap	West	Crack (1)	
	Cap	South	Multiple cracks (2)	

Figure 4A. Condition of Bent No. 5 (East Bound).

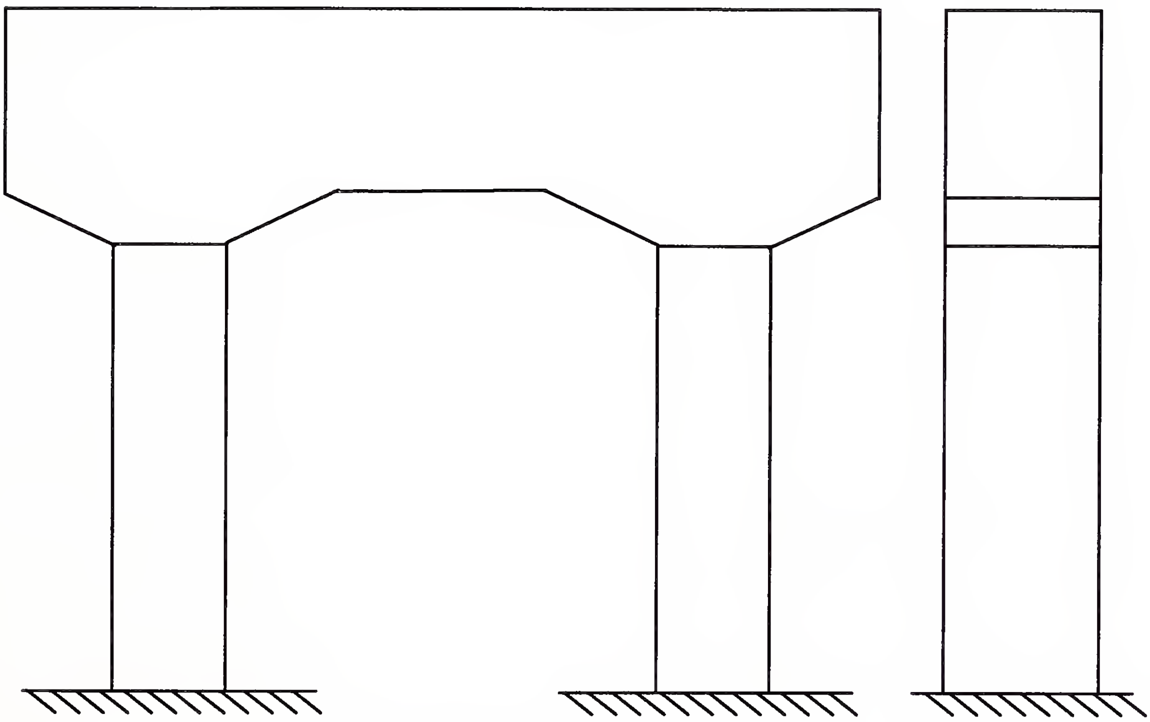


Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage
	Cap	South	Two cracks (1)	
	Cap	North	A crack (2)	
	S. Col.	East	Two cracks and delamination (3)	Test Performed: None

Figure 5A. Condition of Bent No. 6 (East Bound).



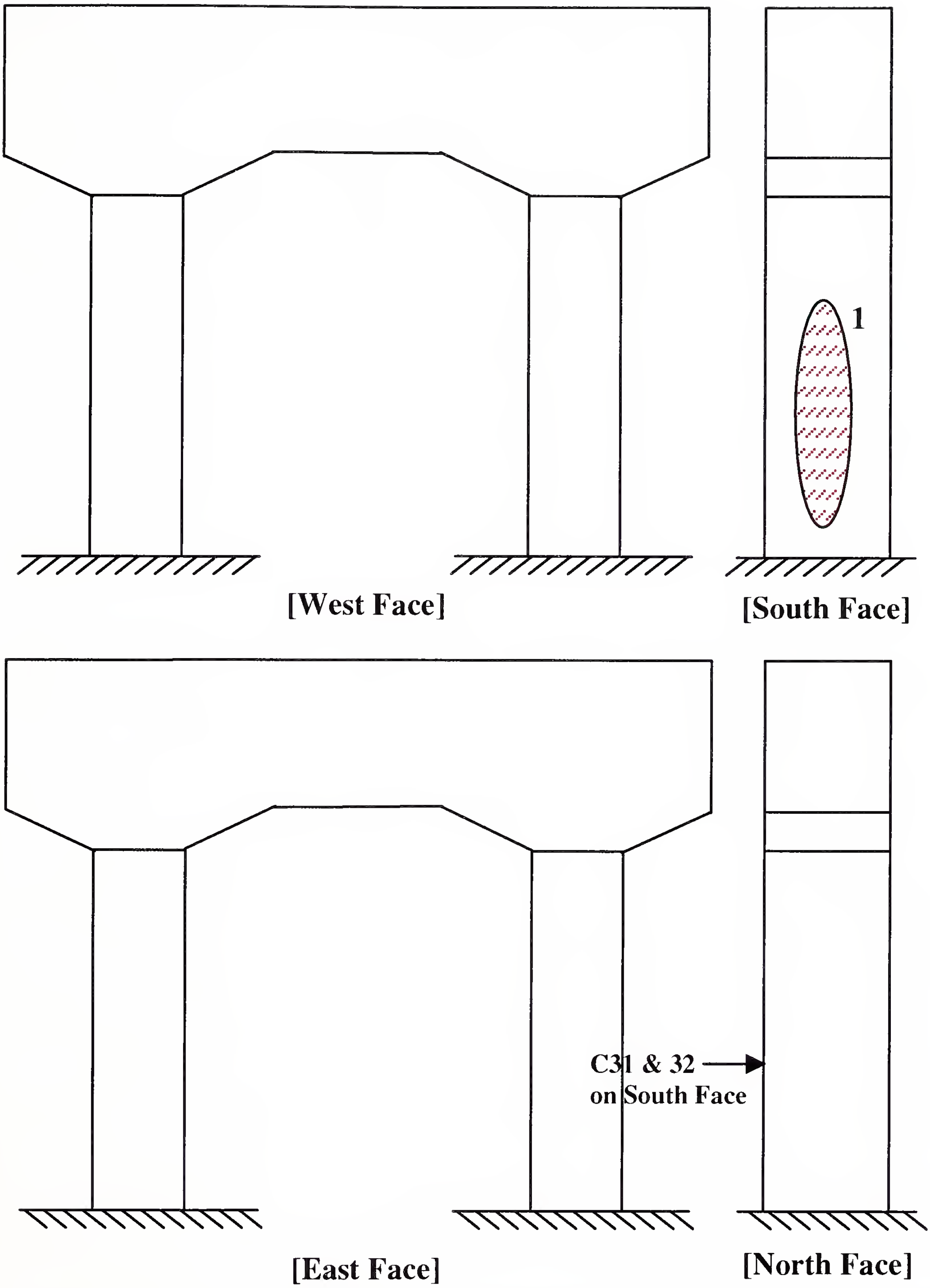
[West Face] [South Face]



[East Face] [North Face]

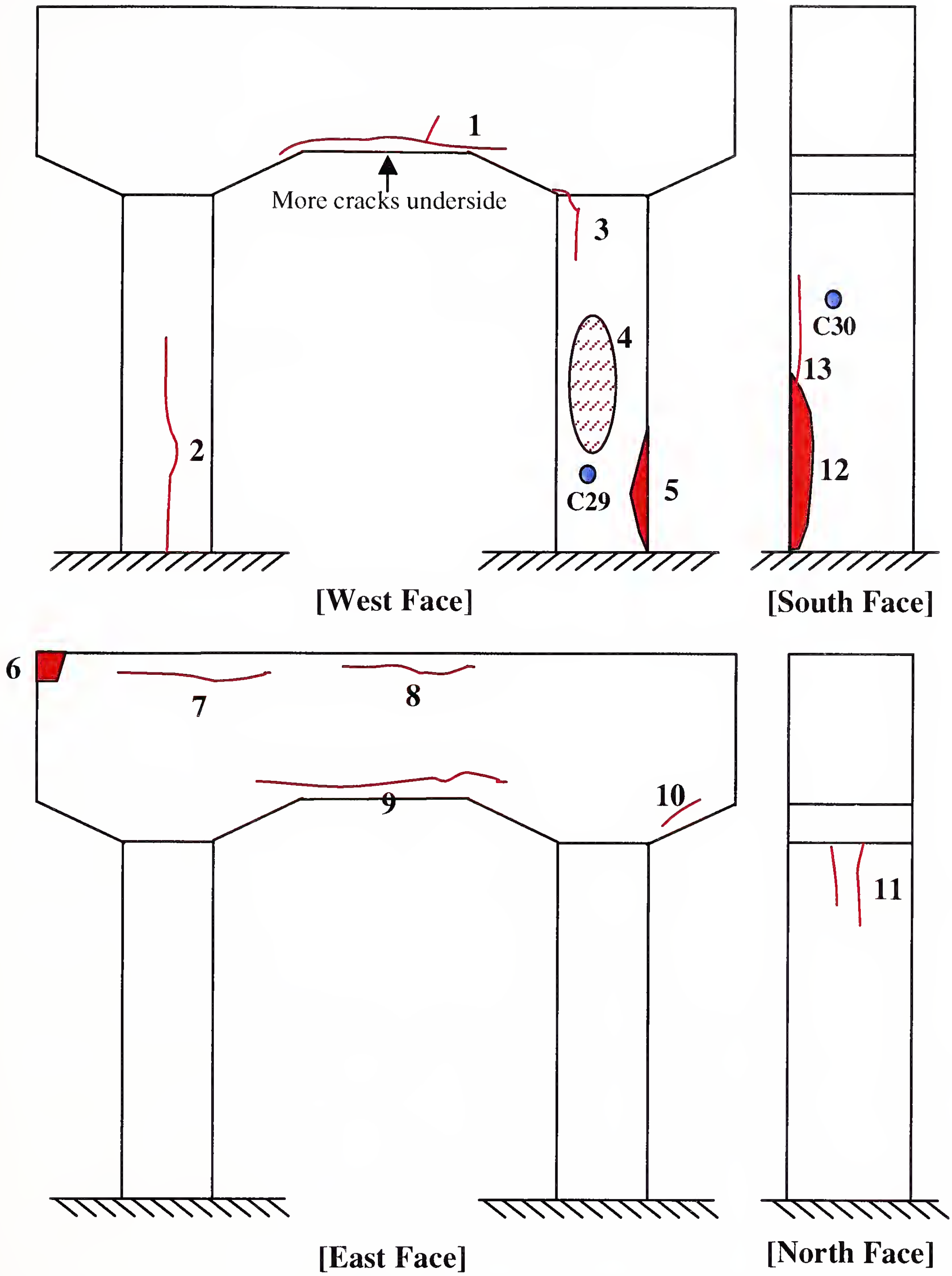
	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but moist
Damage	Cap	West	Small spall (1)	
				Test Performed: None

Figure 6A. Condition of Bent No. 7 (East Bound).



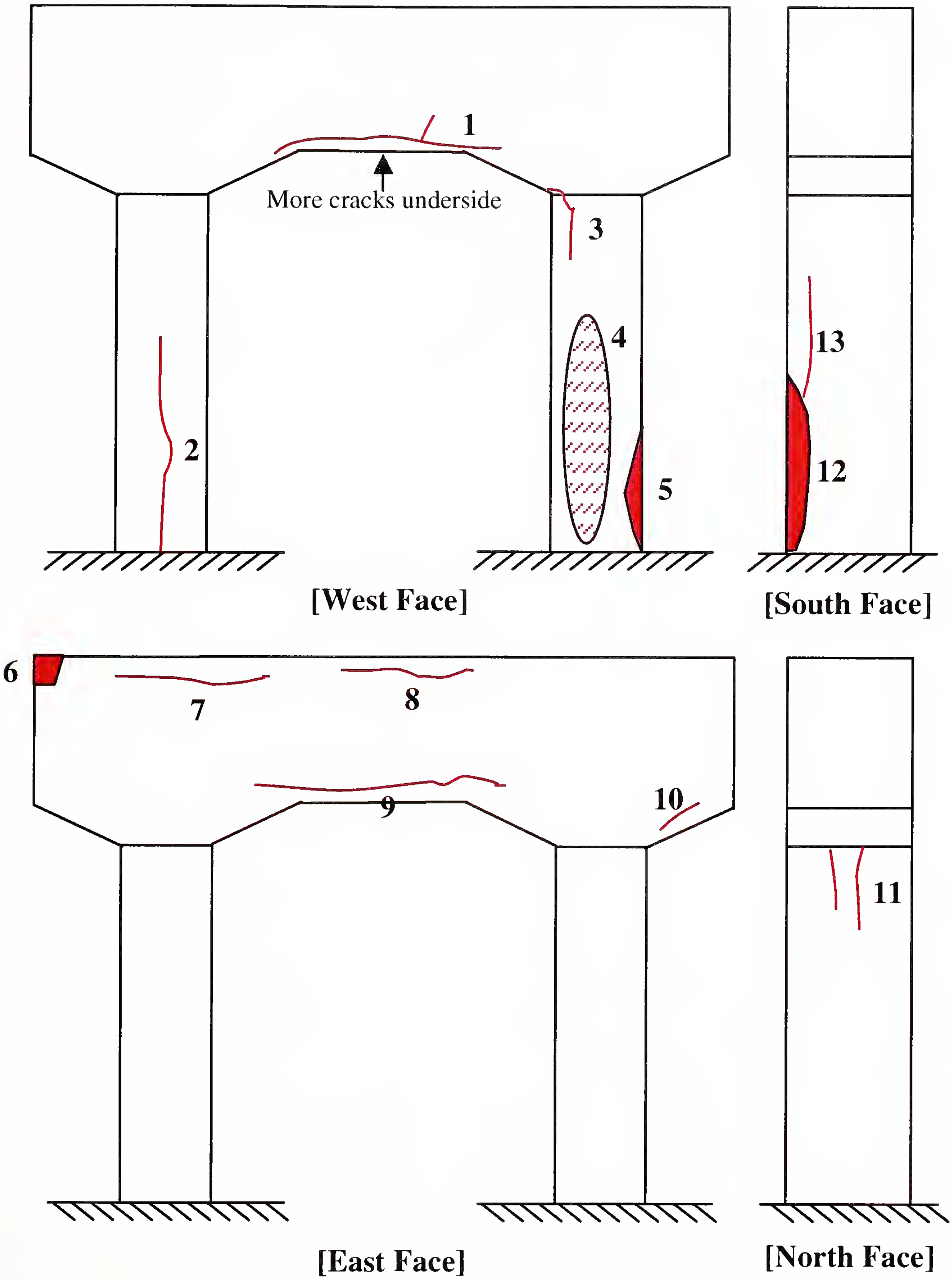
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage Test Performed: Cores 31-32
	S. Col.	South	Multiple cracks (1)	

Figure 7A. Condition of Bent No. 8 (East Bound).



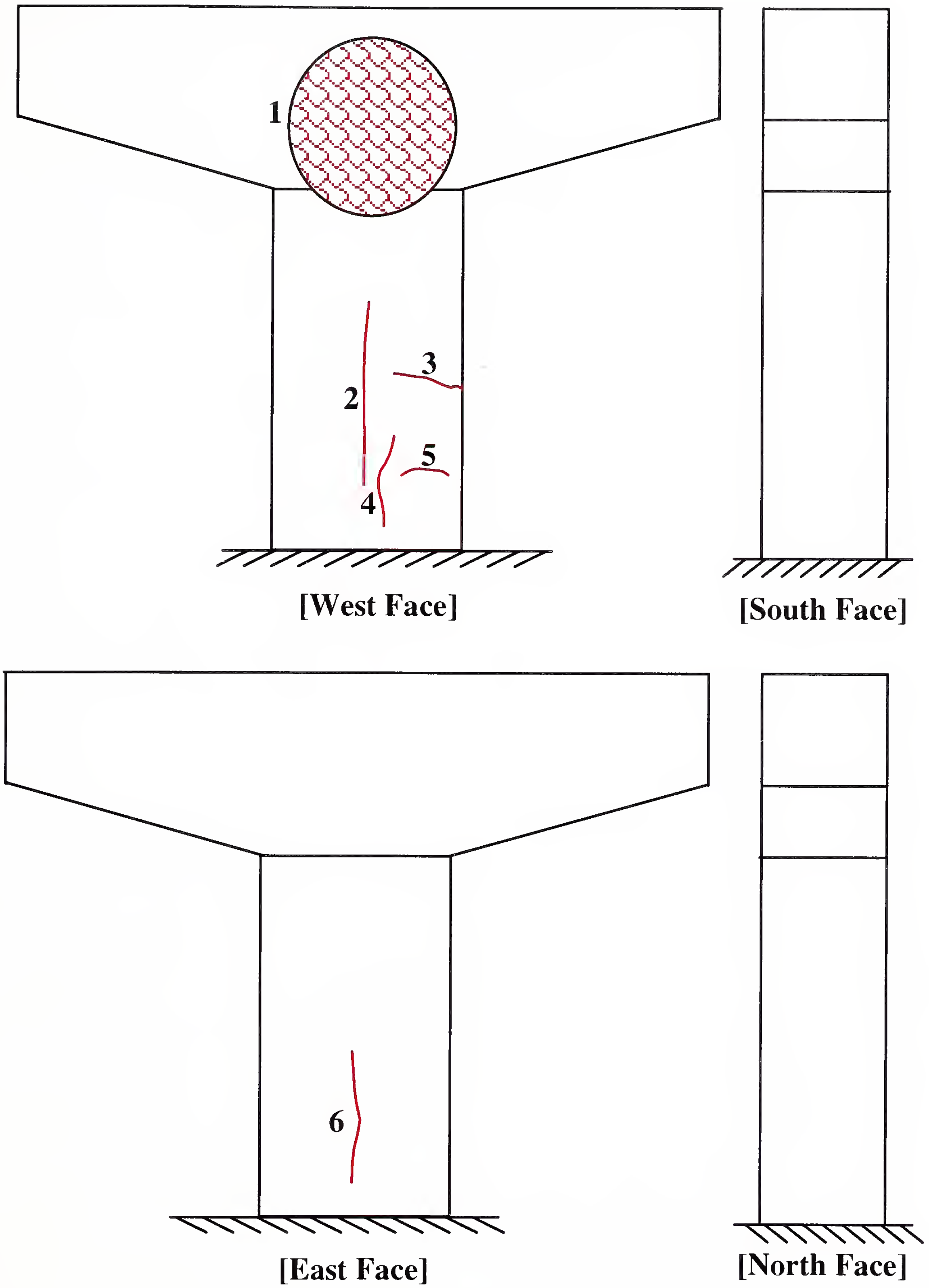
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but concrete exhibits dark stains Test Performed: Core 29-30
	Cap	West	Multiple cracks (1)	
	S. Col.	West	A crack (2)	
	N. Col.	West	A crack (3)	
	N. Col.	West	Multiple cracks (4)	
	N. Col.	West	Spall (5)	

Figure 8A.1. Condition of Bent No. 9 (East Bound) - To Be Continued.



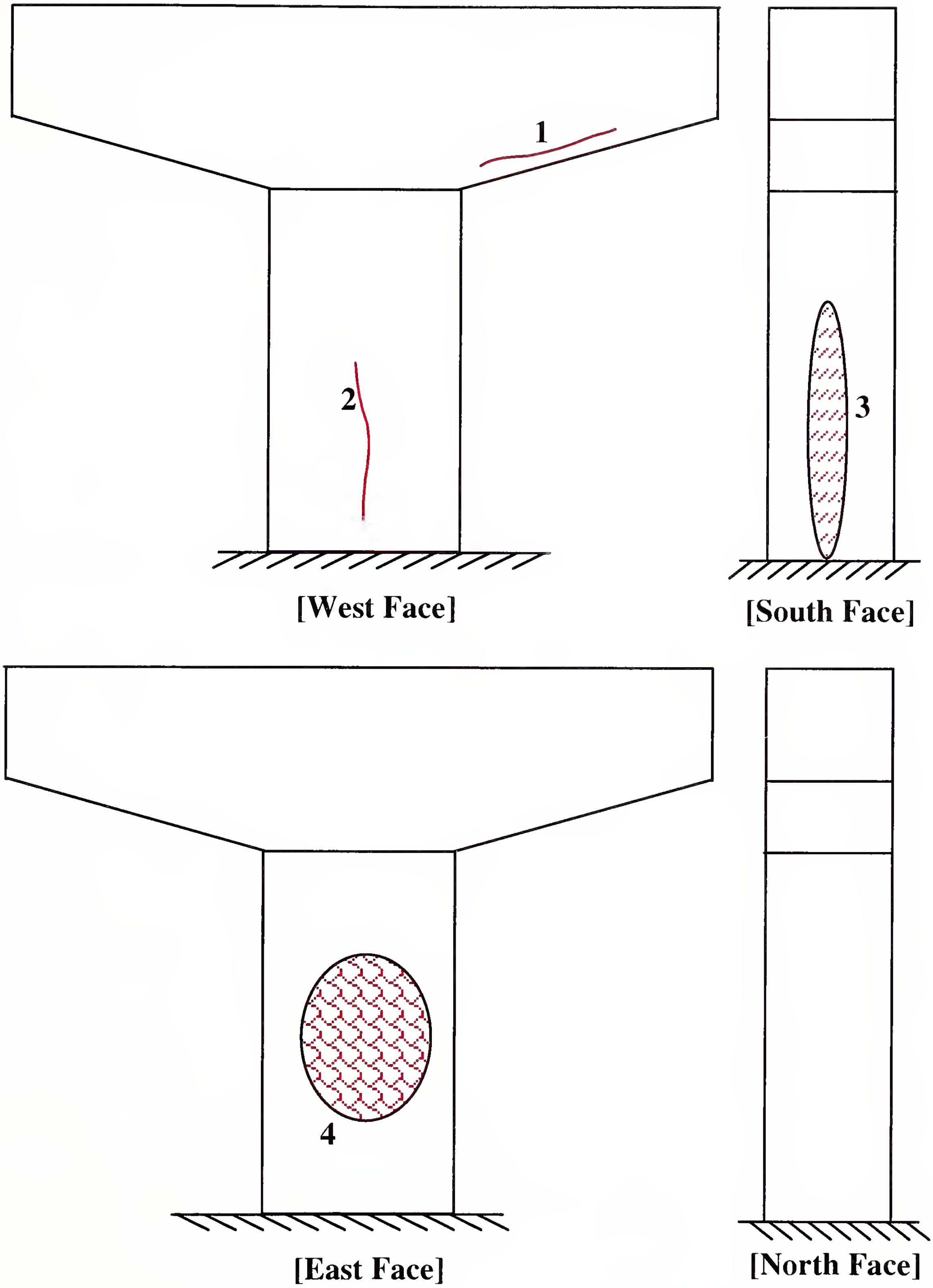
	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but concrete exhibits dark stains Test Performed: None
Damage	Cap	East	Small spall (6)	
	Cap	East	Cracks (7-10)	
	N. Col.	North	Two crack (11)	

Figure 8A.2. Condition of Bent No. 9 (East Bound) - Continued.



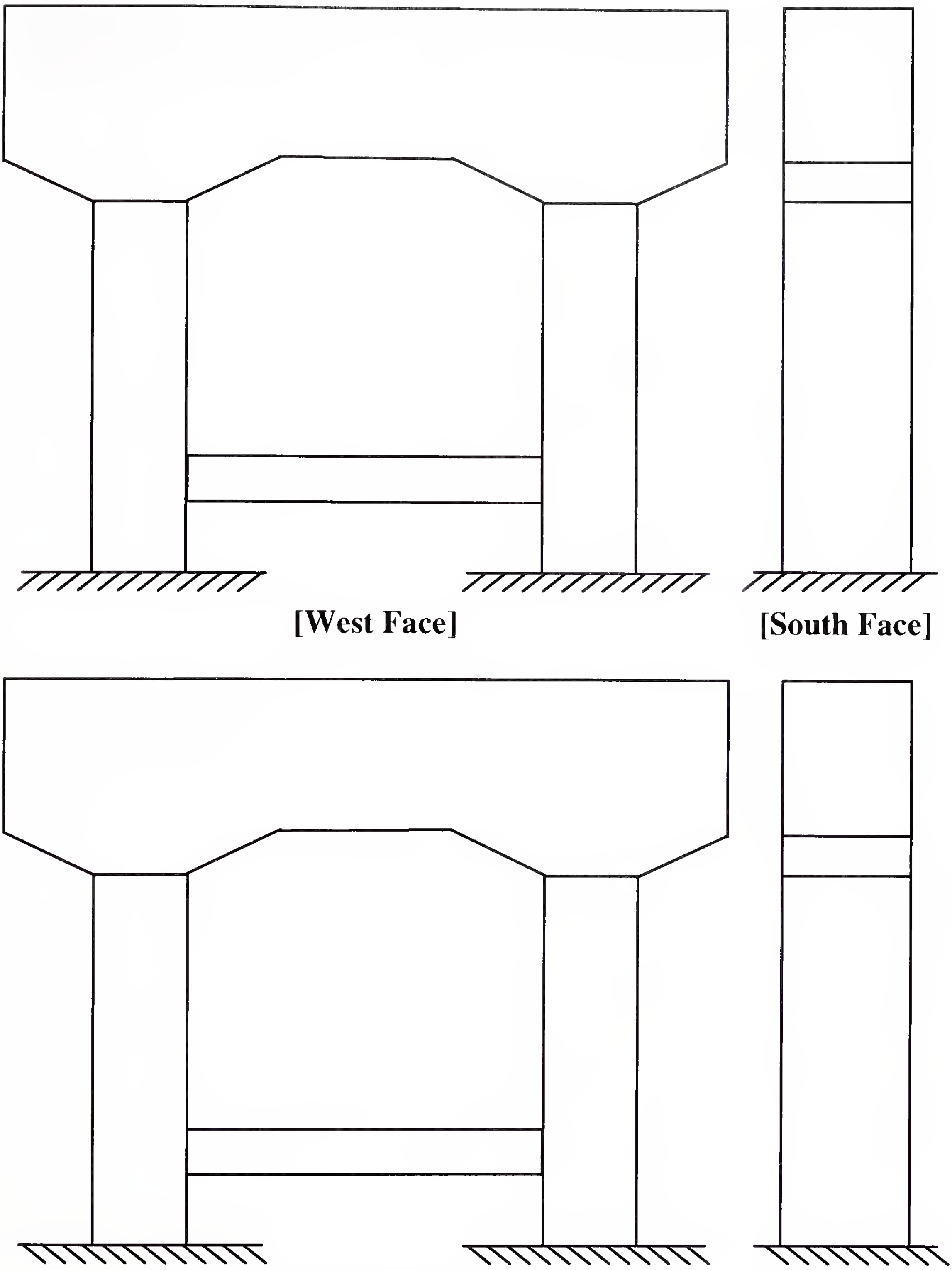
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage below beams 1-2, 2-3, 3-4 Test Performed: None
	Cap/Col.	West	Pattern cracking (1)	
	Column	West	Cracks (2-5)	
	Column	East	Cracks (6)	

Figure 9A. Condition of Bent No. 10 (East Bound).



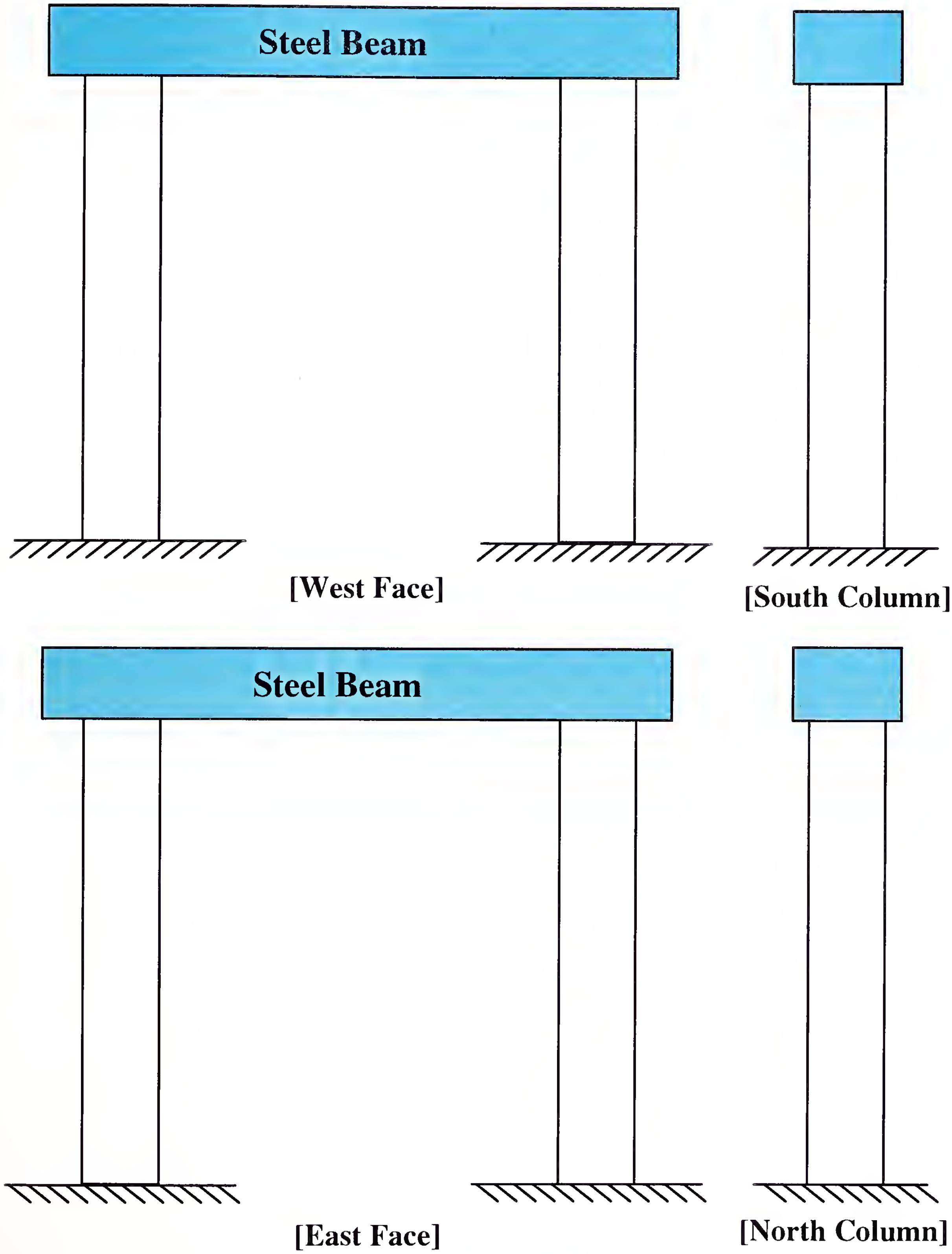
	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage at center and north side worst Test Performed: None
Damage	Cap	West	A crack (1)	
	Column	West	A crack (2)	
	Column	South	Pattern cracking (3)	
	Column	East	Pattern cracking (4)	

Figure 10A. Condition of Bent No. 11 (East Bound).



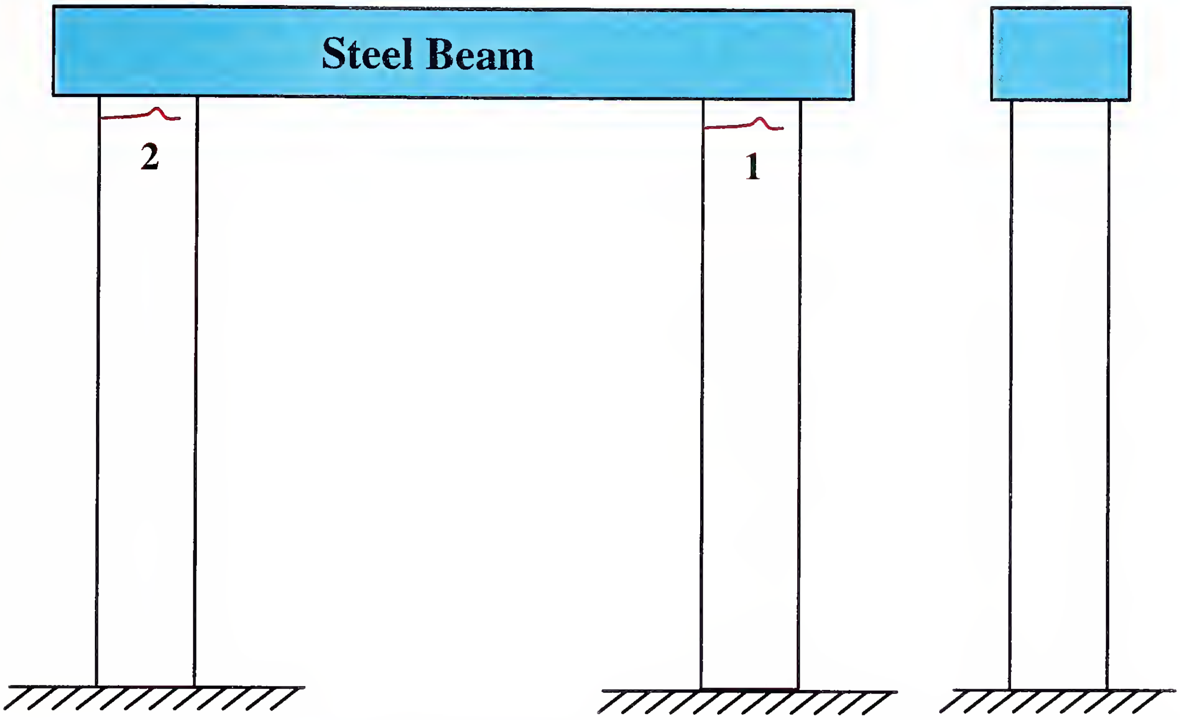
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage
		No Damage Observed		Test Performed: None

Figure 11A. Condition of Bent No. 12 (East Bound).

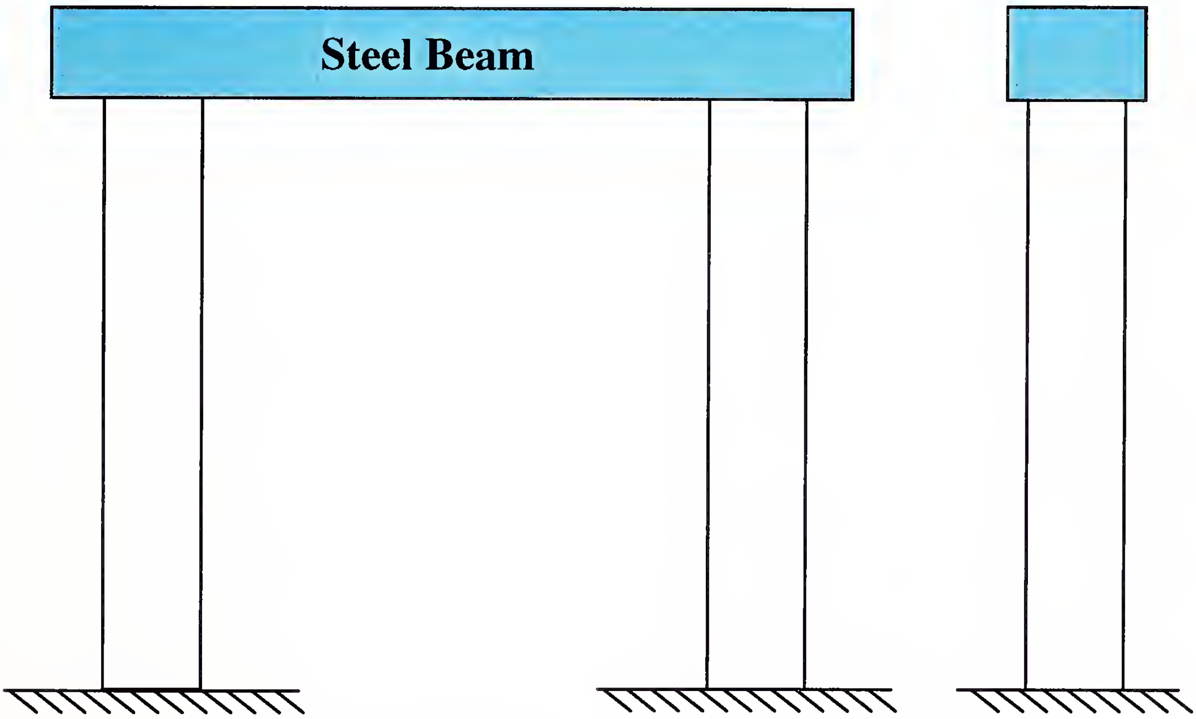


Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No deck above and exposed
	No apparent damage observed but pattern cracking on the entire surface of two columns (North column appeared to be worse than South one).			Test Performed: None

Figure 12A. Condition of Bent No. 13 (East Bound).



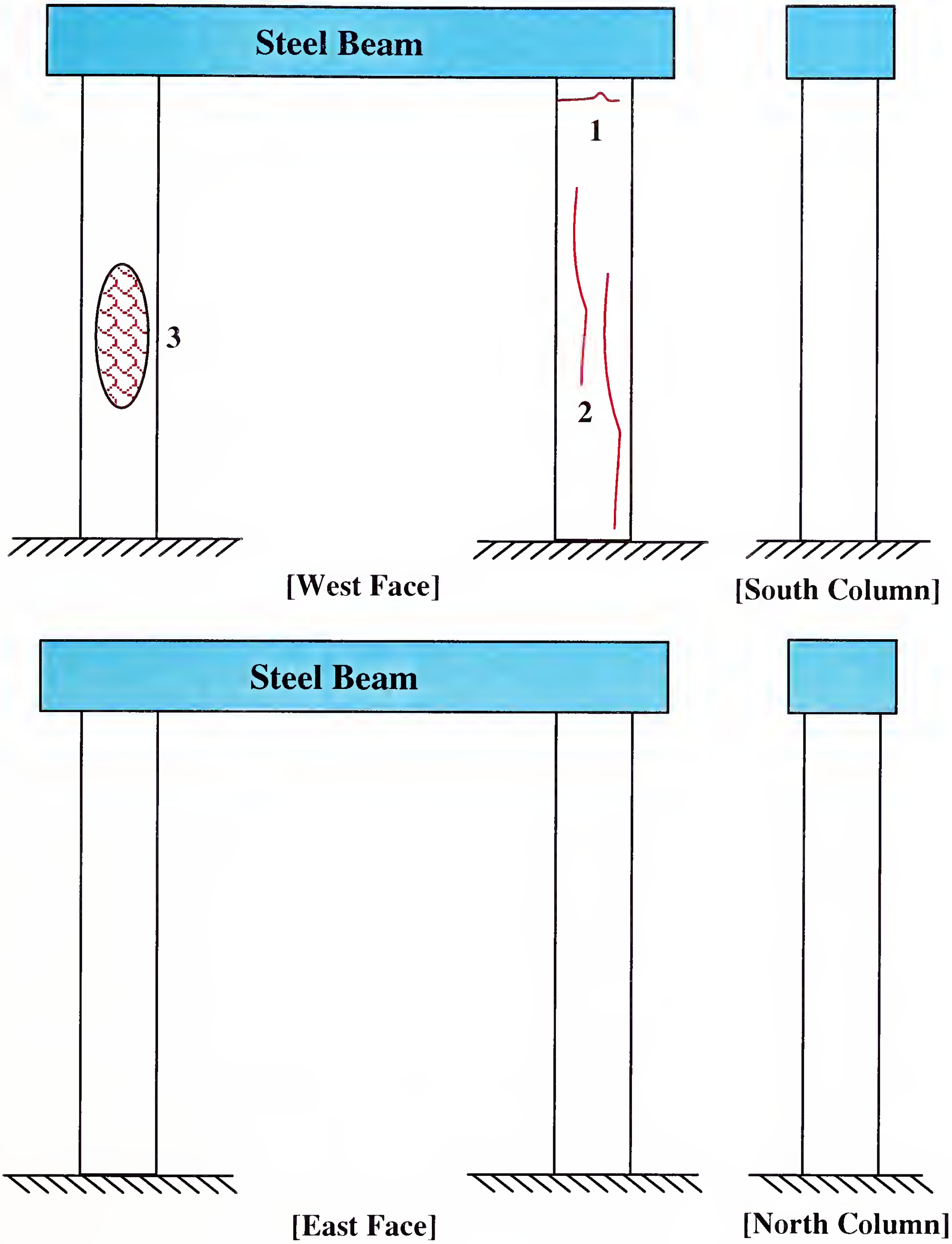
[West Face] [South Column]



[East Face] [North Circular column]

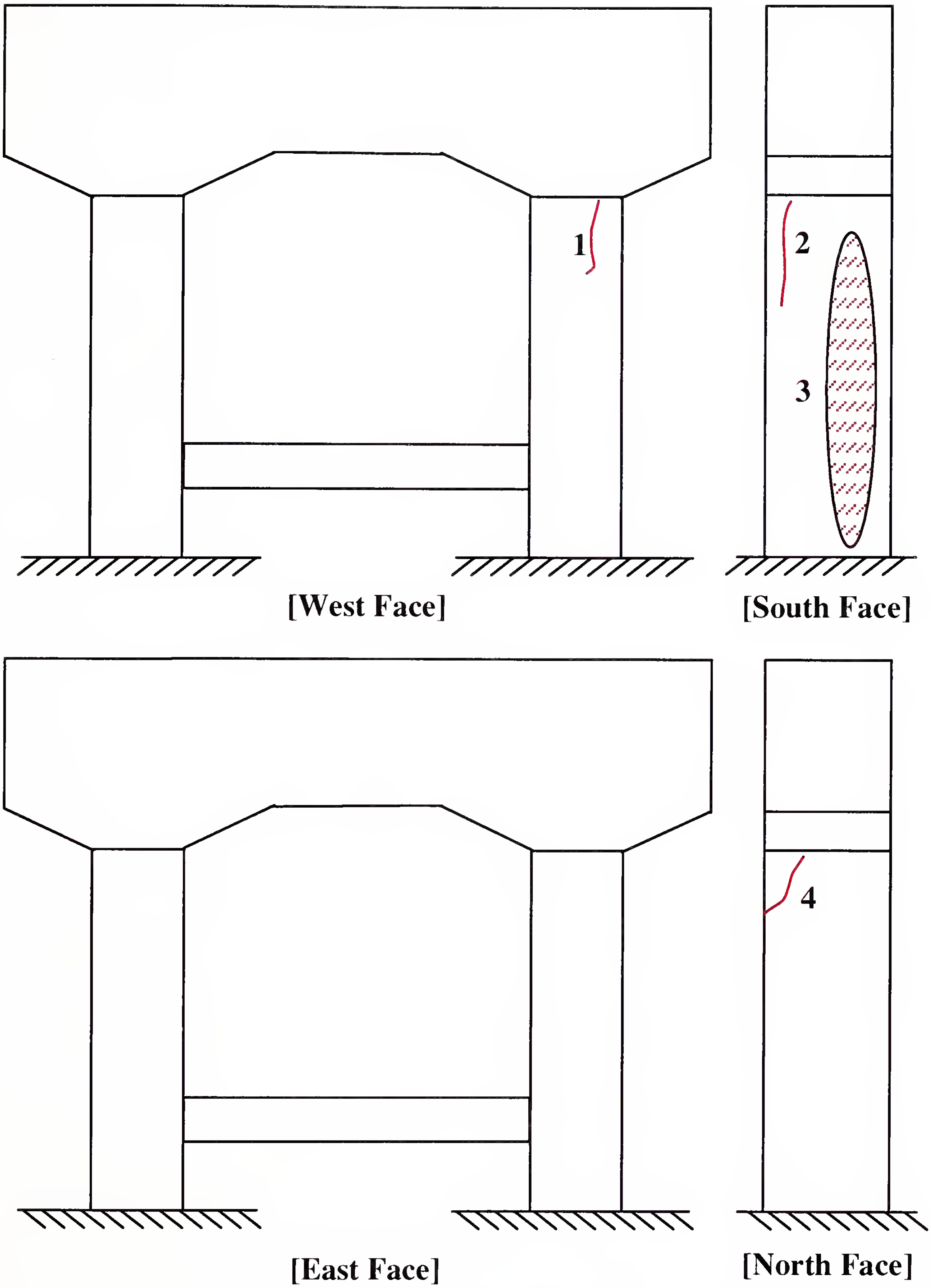
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No deck above and exposed Test Performed: None
	Column	Circular	Cracks (1-2)	
	Pattern cracking and large cracks on large surface area of both columns (North column appeared to be worse than South one).			

Figure 13A. Condition of Bent No. 14 (East Bound).



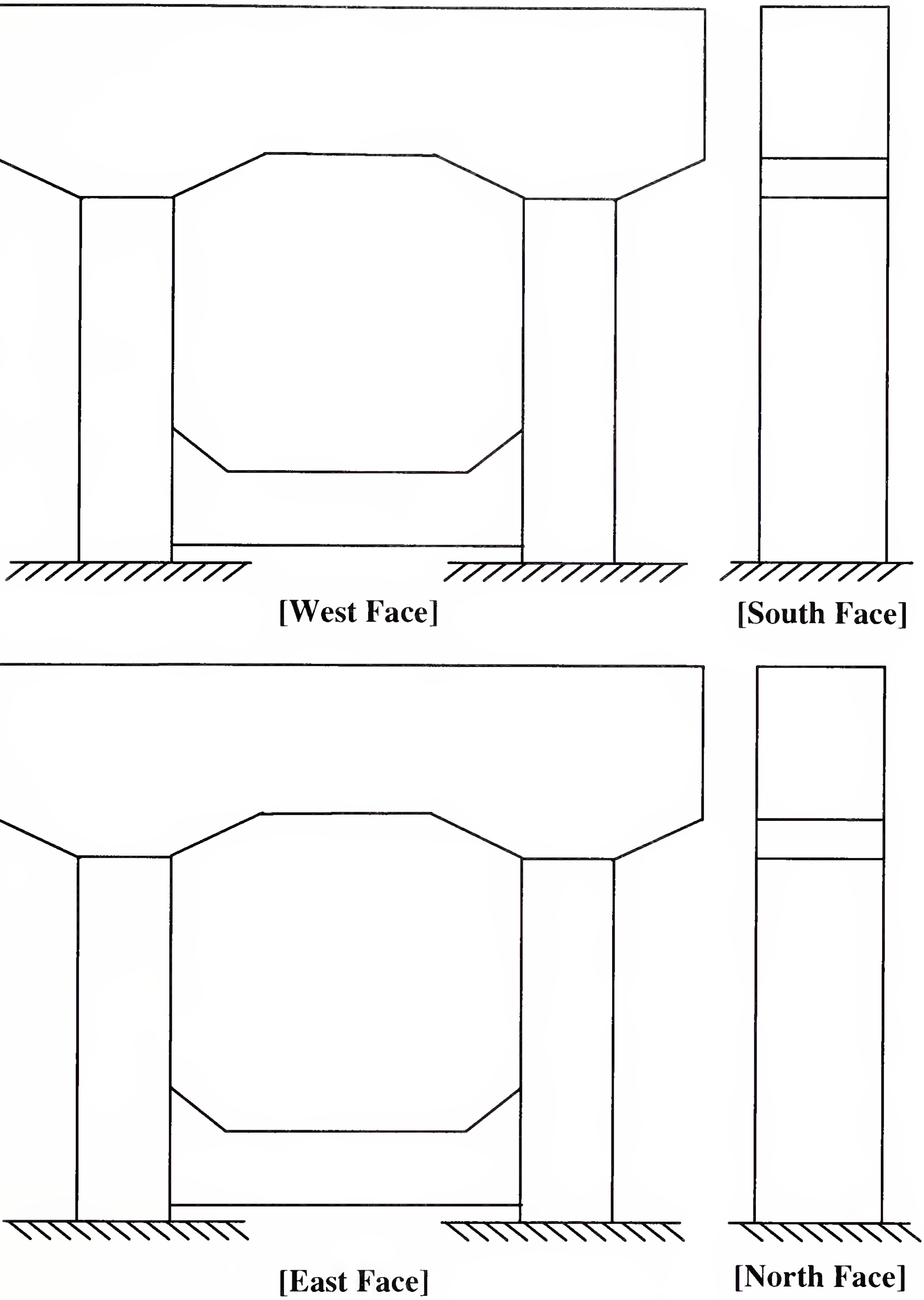
	Location	Face	Description of Damage (No.)	Leakage Condition: No deck above and exposed Test Performed: None
Damage	Column	Circular	Cracks (1-2)	
	Column	Circular	Pattern cracking (3)	

Figure 14A. Condition of Bent No. 15 (East Bound).



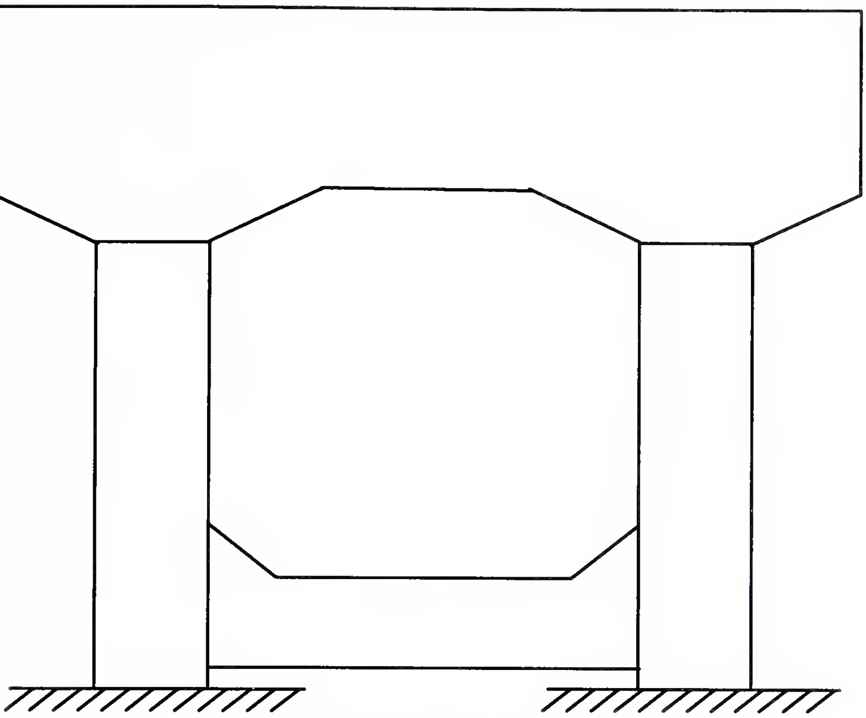
	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage
Damage	Column	West	Crack (1)	
	Column	South	Crack (2)	
	Column	South	Multiple cracks (3)	Test Performed: None
	Column	North	Crack (4)	

Figure 15A. Condition of Bent No. 16 (East Bound).

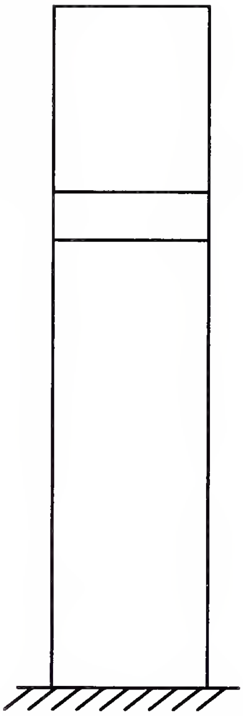


Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage
			No Damage Observed	Test Performed: None

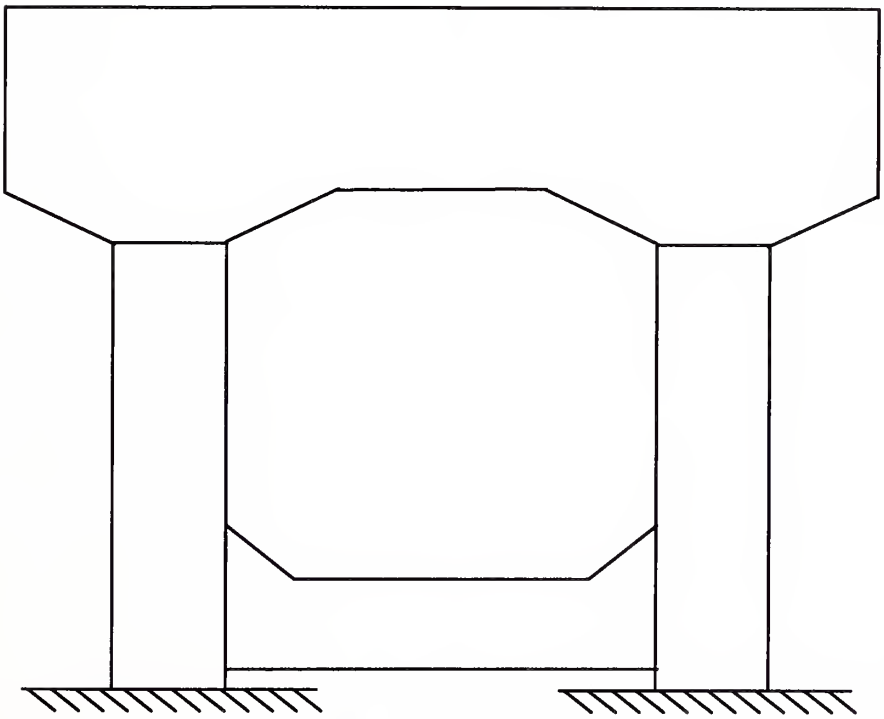
Figure 16A. Condition of Bent No. 17 (East Bound).



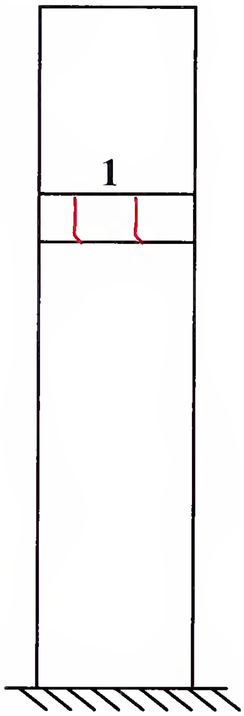
[West Face]



[South Face]



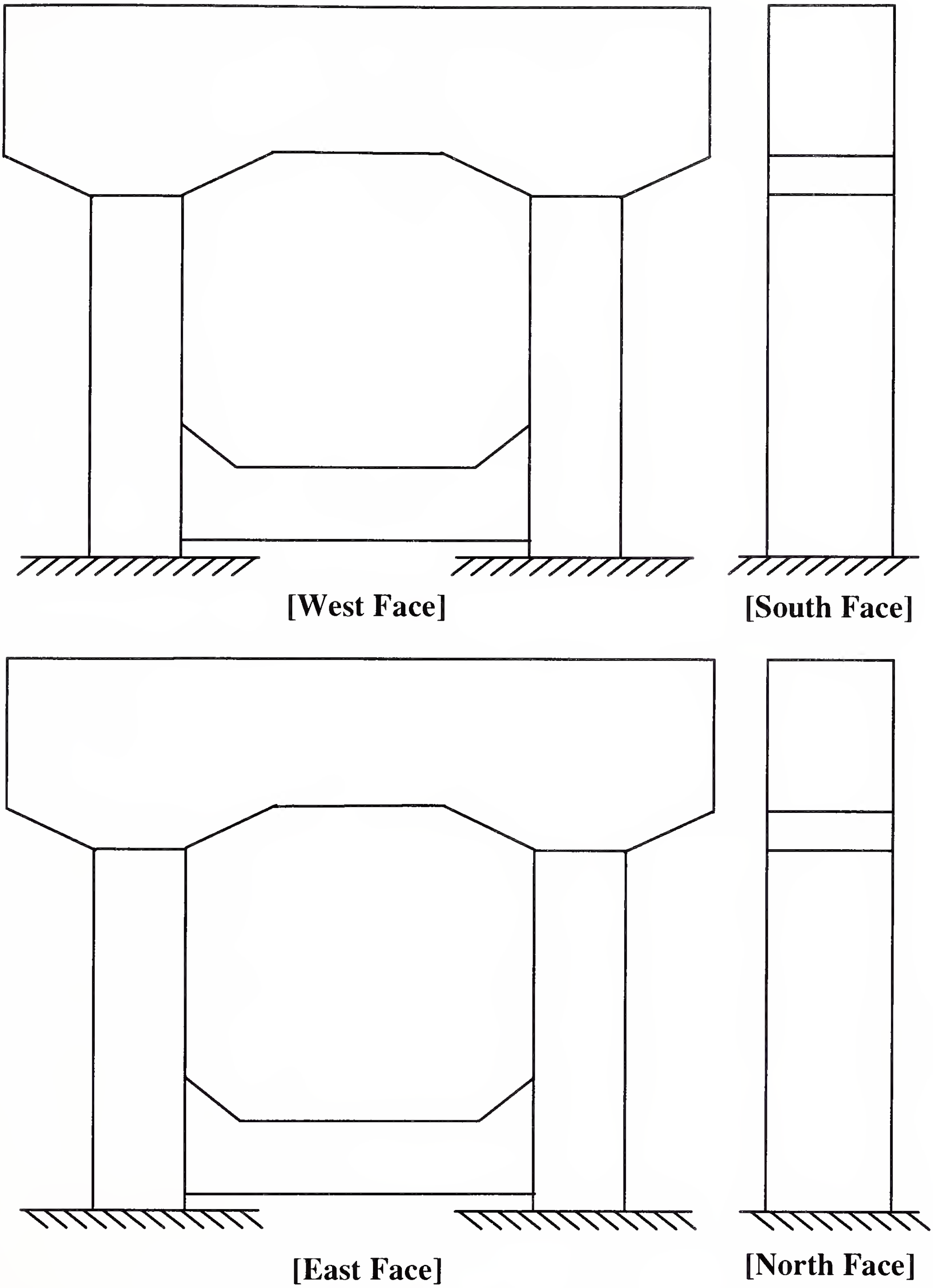
[East Face]



[North Face]

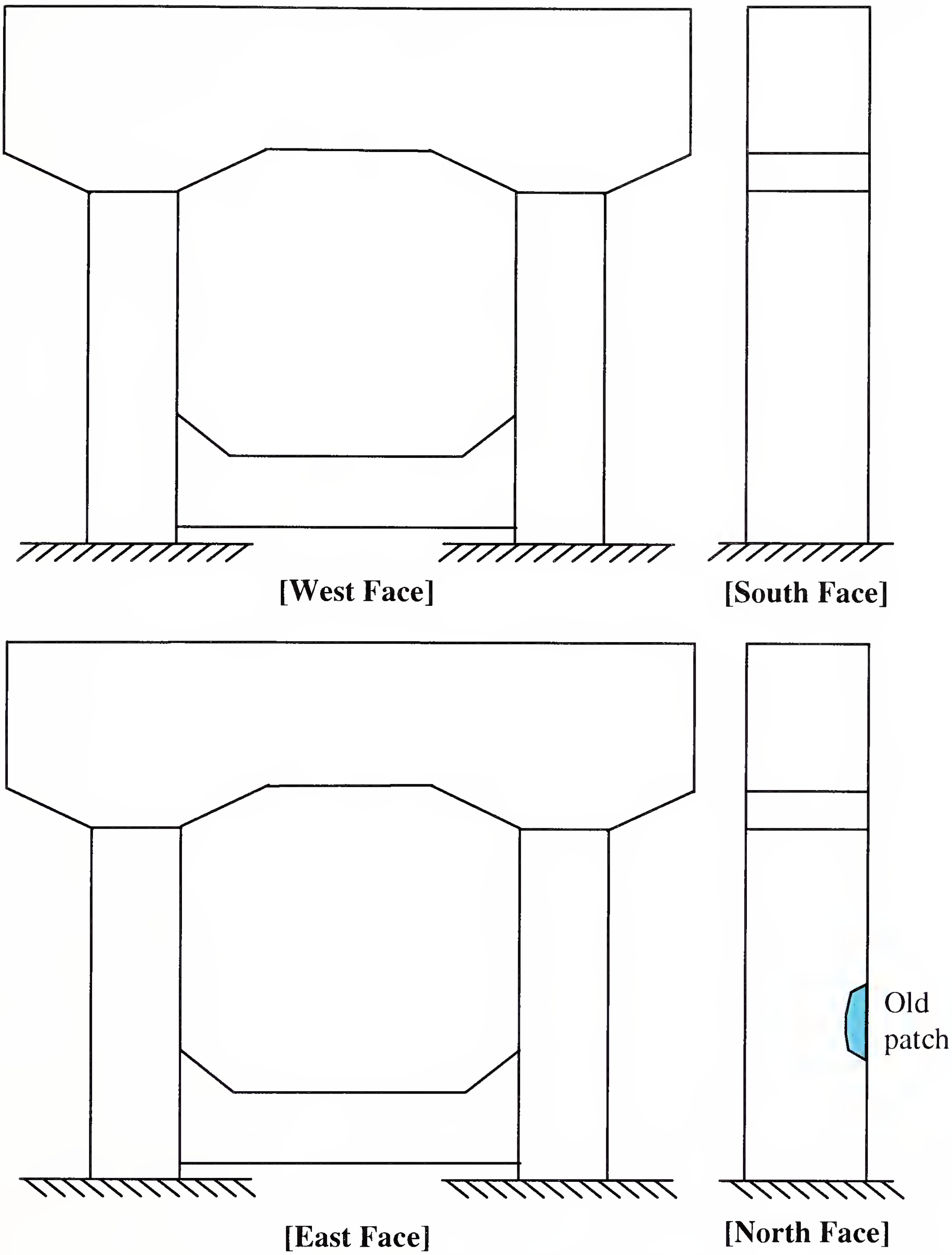
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage Test Performed: None
	N. Col.	North	Two cracks (1)	

Figure 17A. Condition of Bent No. 18 (East Bound).



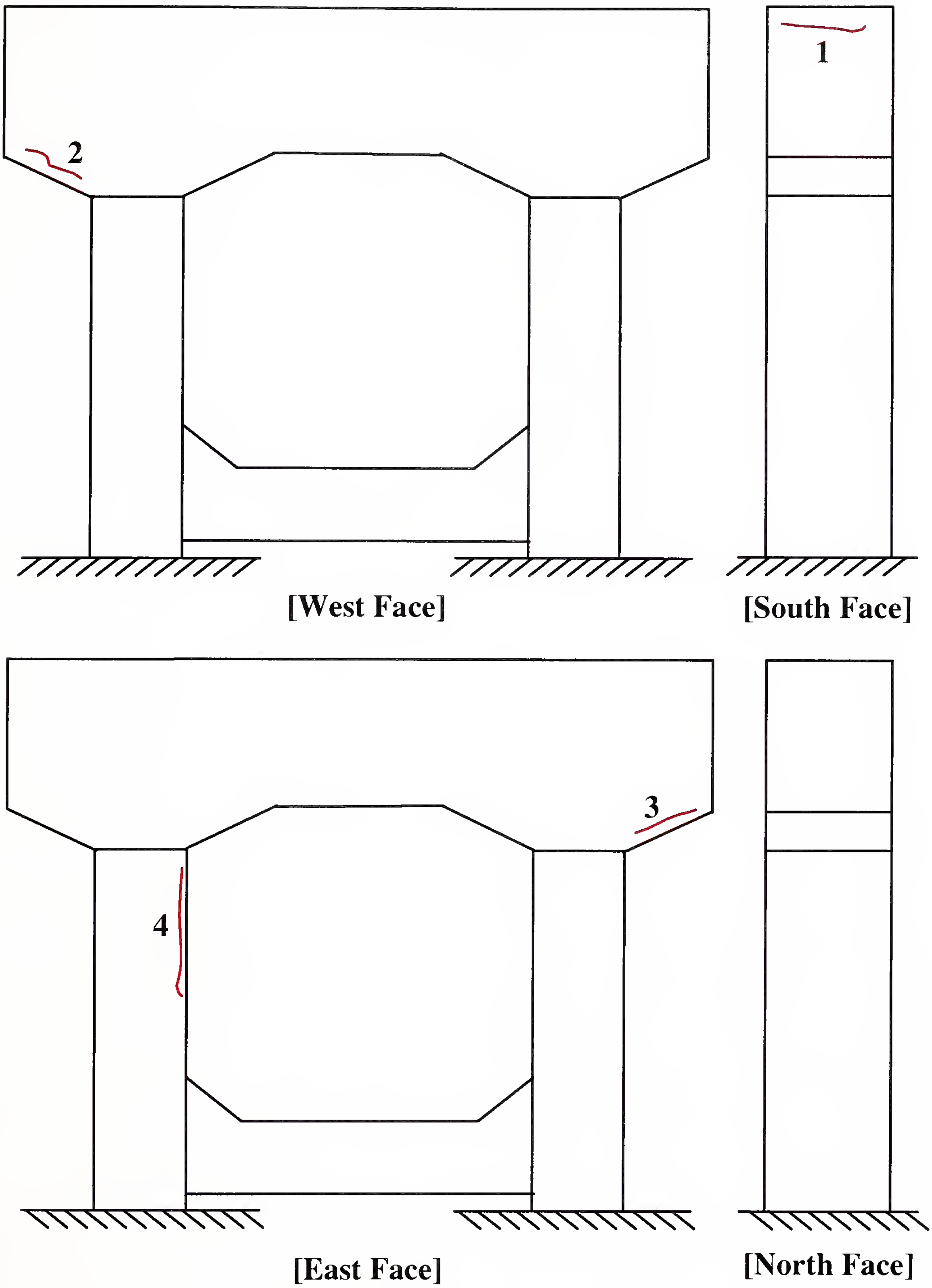
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Moist below beams 2-5 Test Performed: None
		No Damage Observed		

Figure 18A. Condition of Bent No. 19 (East Bound).



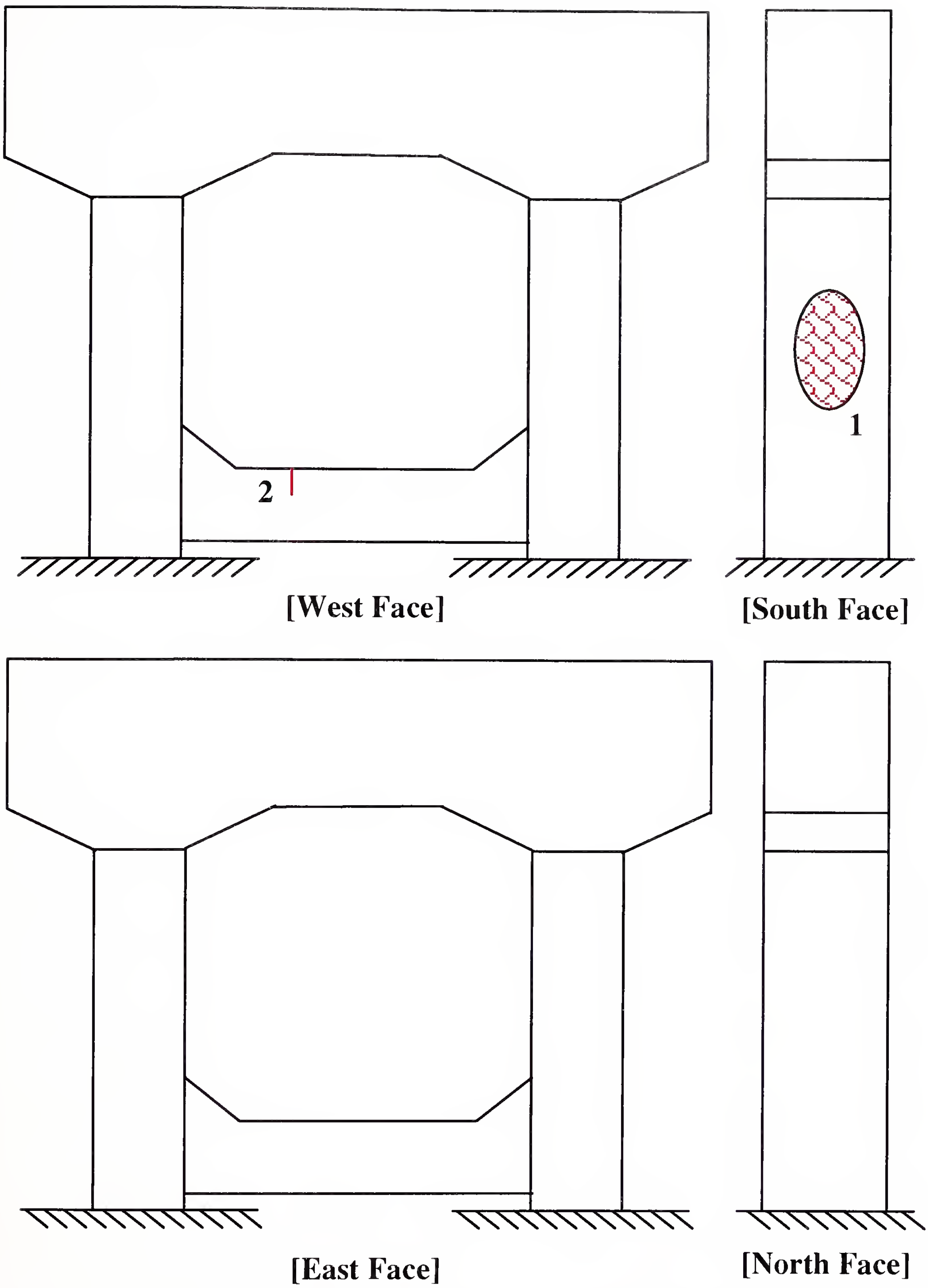
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Moist below beams 2-5 Test Performed: None
		No Damage Observed		

Figure 19A. Condition of Bent No. 20 (East Bound).



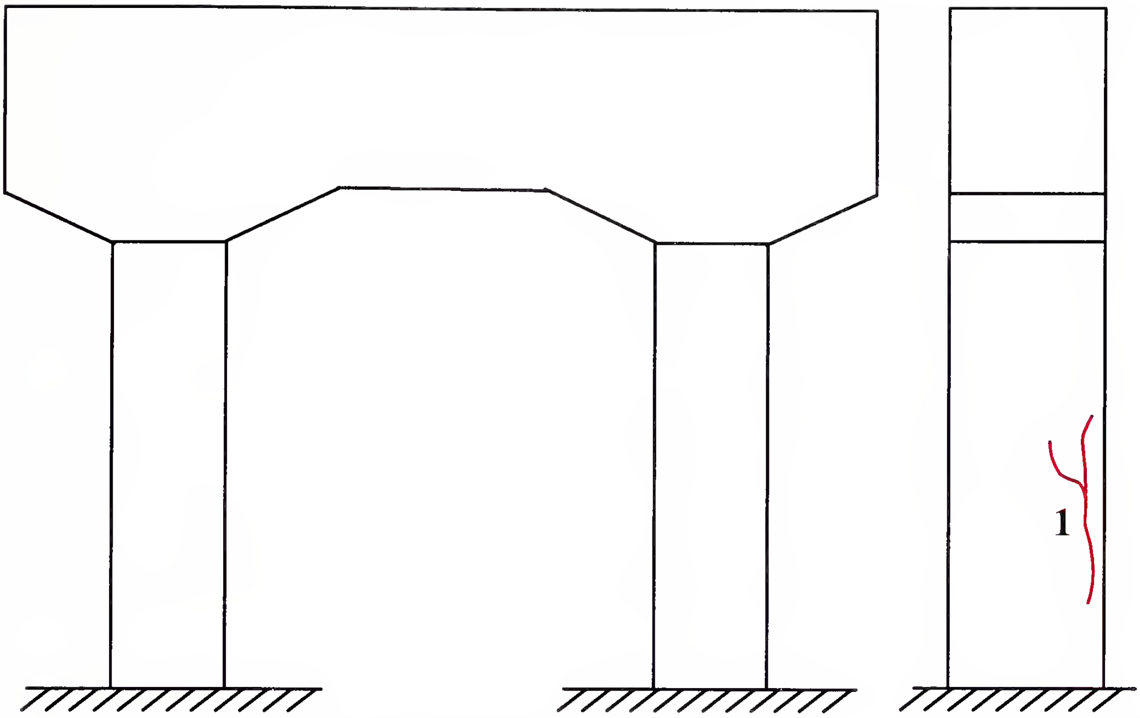
	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but dry stains Test Performed: None
Damage	S. Col.	South	A crack and dry stains (1)	
	Cap	West	A crack (2)	
	Cap	East	A crack (3)	
	S. Col.	East	A crack along the edge(4)	

Figure 20A. Condition of Bent No. 21 (East Bound).

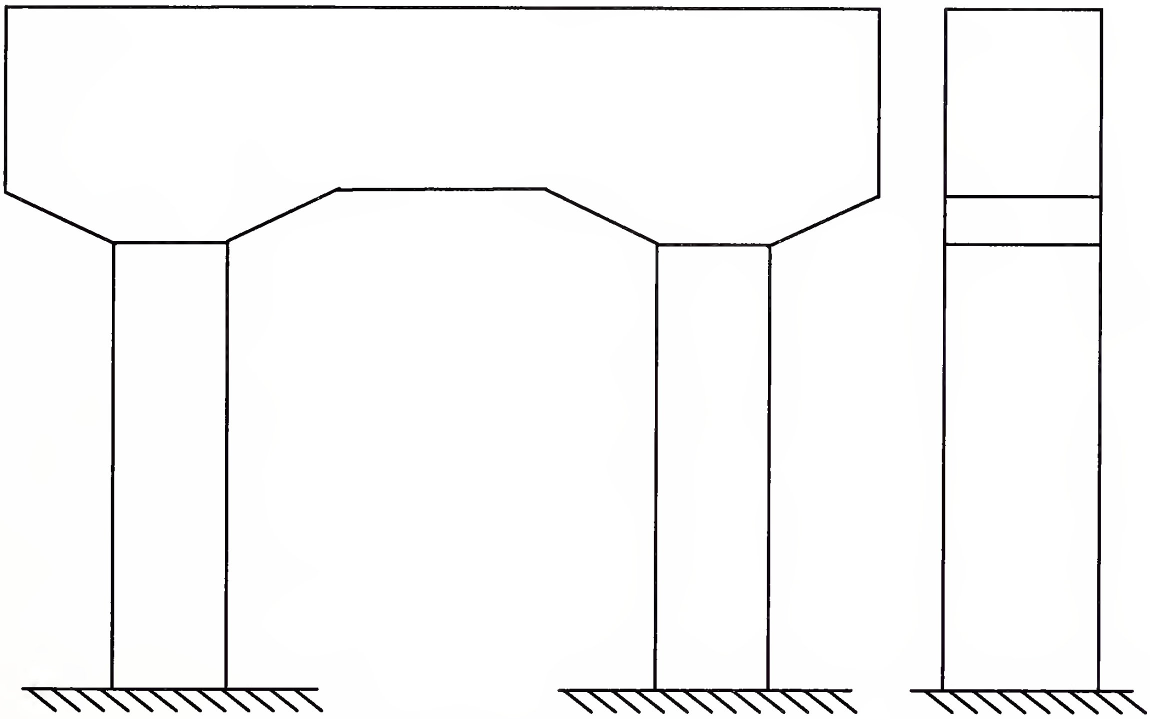


Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage Test Performed: None
	S. Col.	South	Pattern cracking (1)	
	Beam	West	A crack (2)	

Figure 21A. Condition of Bent No. 22 (East Bound).



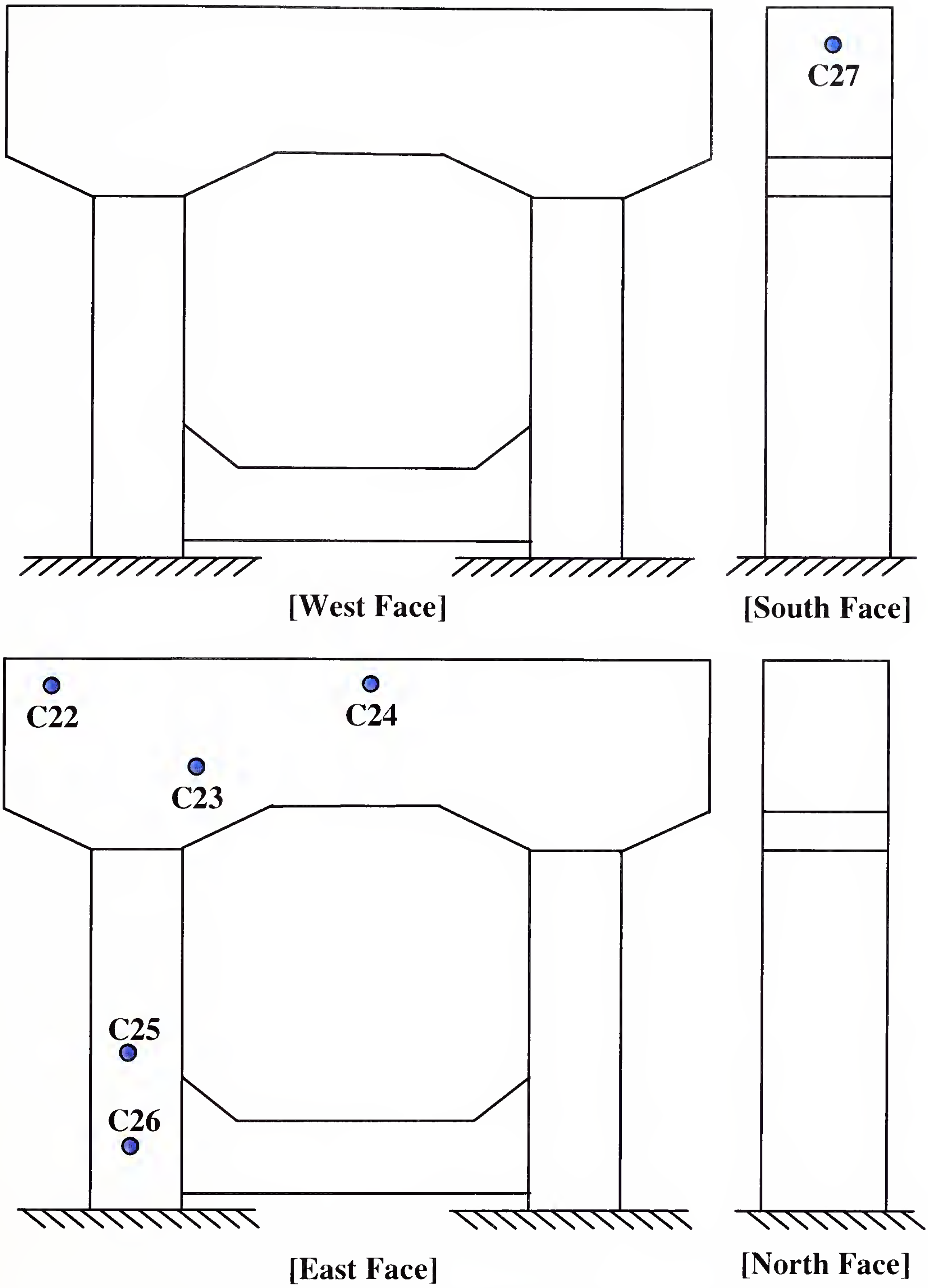
[West Face] [South Face]



[East Face] [North Face]

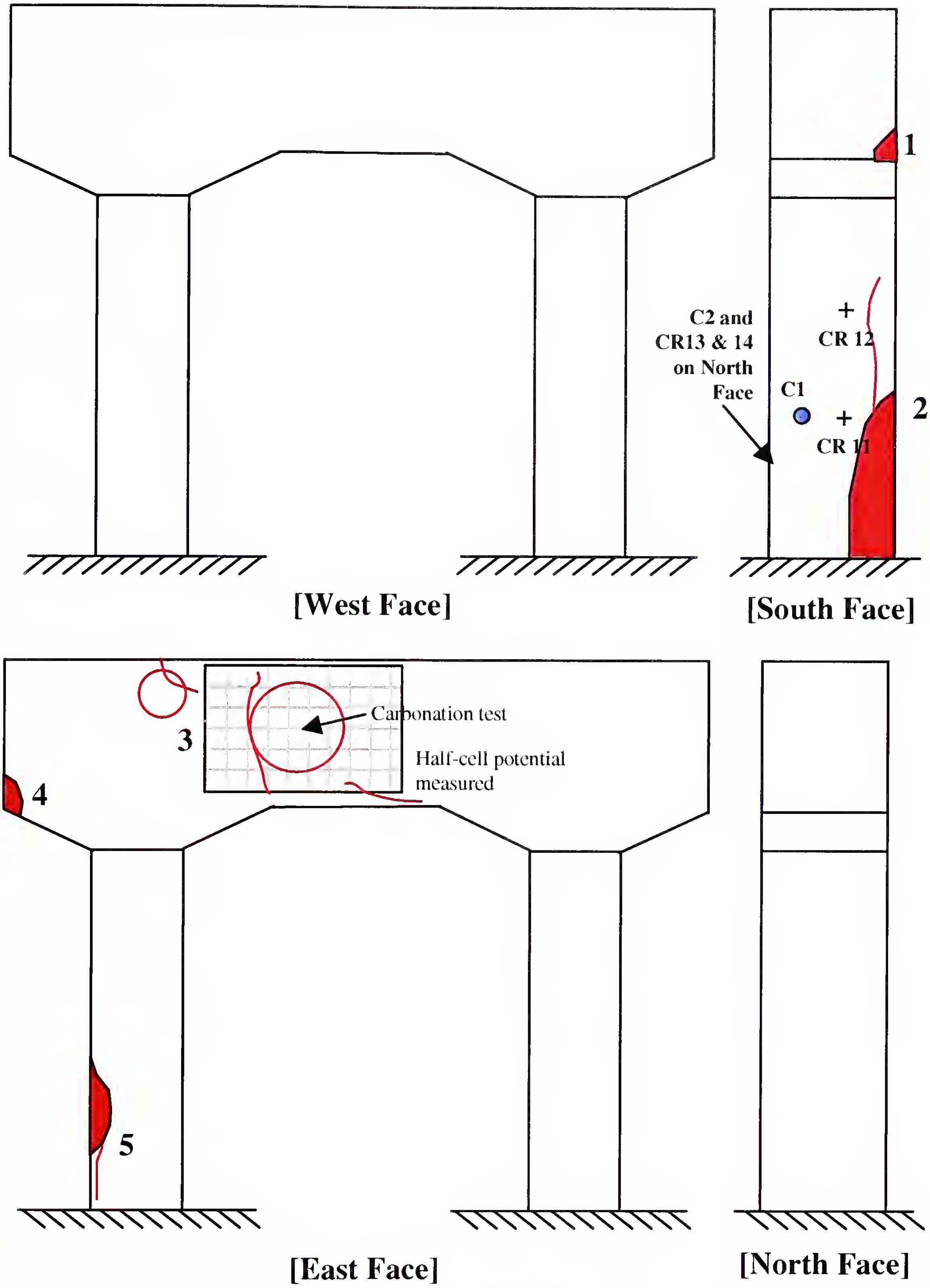
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Joint moist, lots of dry stains on cap Test Performed: None
	S. Col.	South	Two crack at SE corner (1)	

Figure 22A. Condition of Bent No. 23 (East Bound).



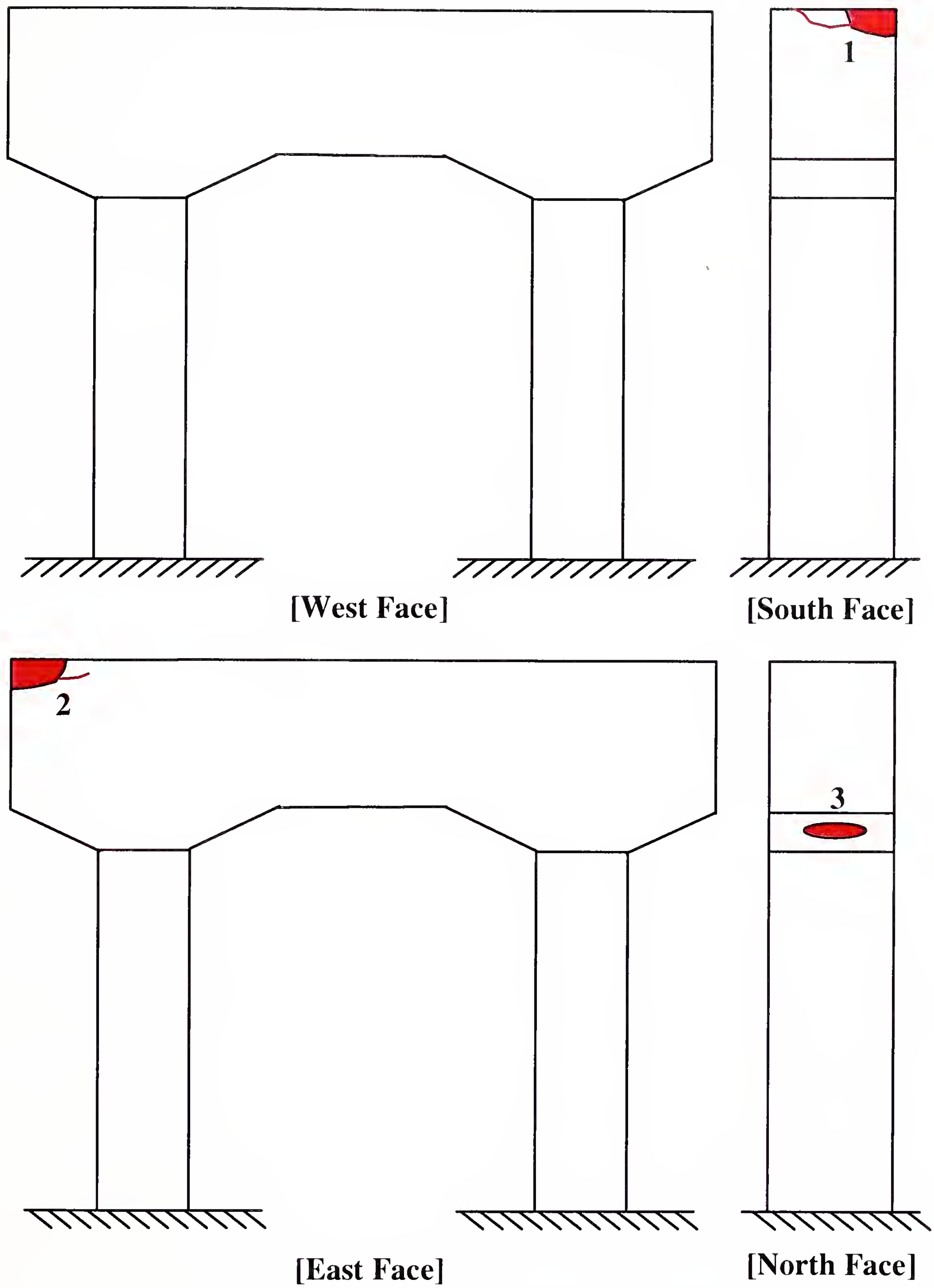
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage
			No Damage Observed	
				Test Performed: Cores: 22-27

Figure 23A. Condition of Bent No. 24 (East Bound).



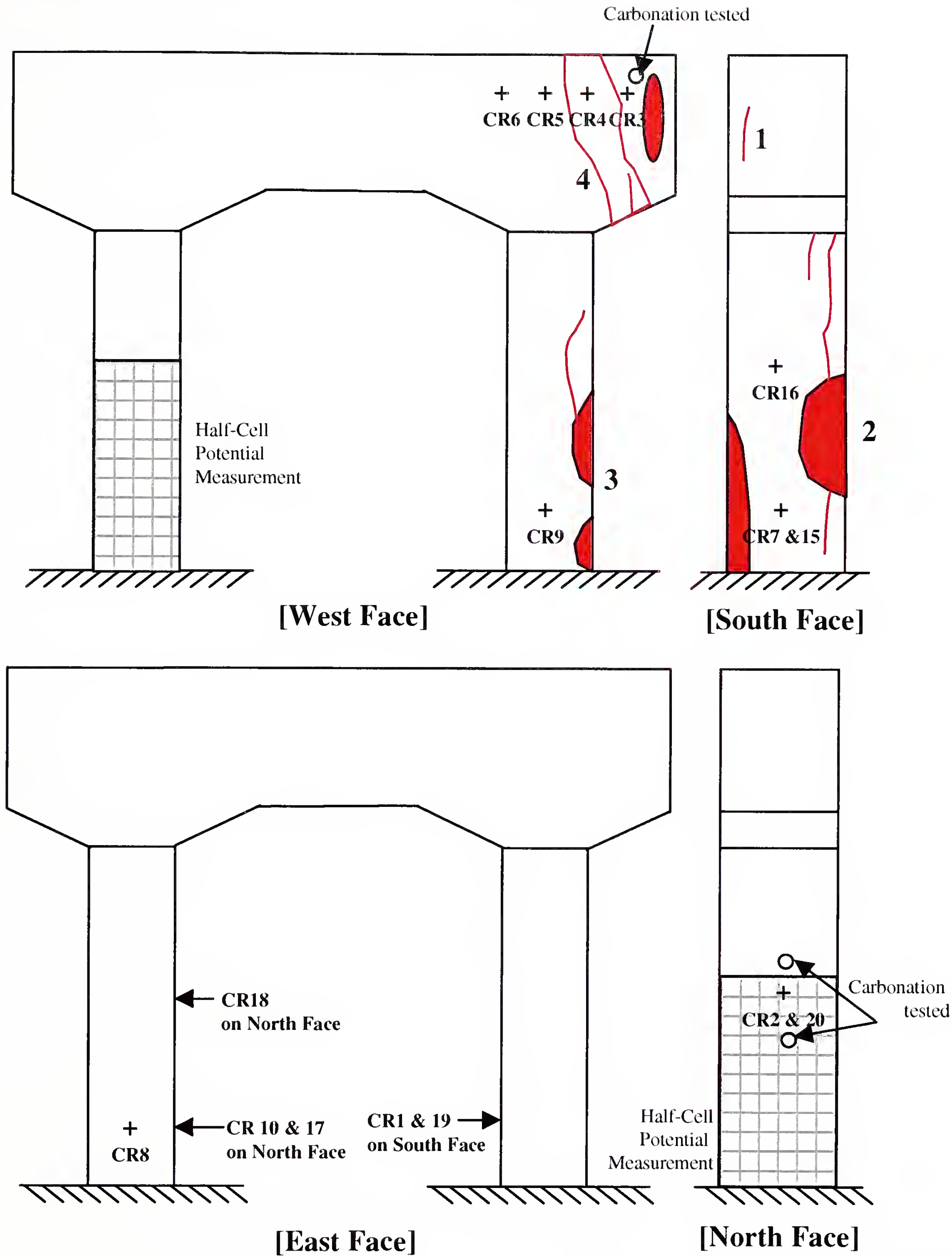
	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage under beams 2-5 Test Performed: - CR 11-14 - Cores 1-2 - Carbonation Test at 3 - Half-Cell Potential
Damage	Cap	South	Small spall exposing a rebar (1)	
	S. Col.	South	Large spall and a crack (2)	
	Cap	East	Two delamination & 3 cracks (3)	
	Cap	East	Small spall (4)	
	S. Col.	East	Medium spall and a crack (5)	

Figure 24A. Condition of Bent No. 25 (East Bound).



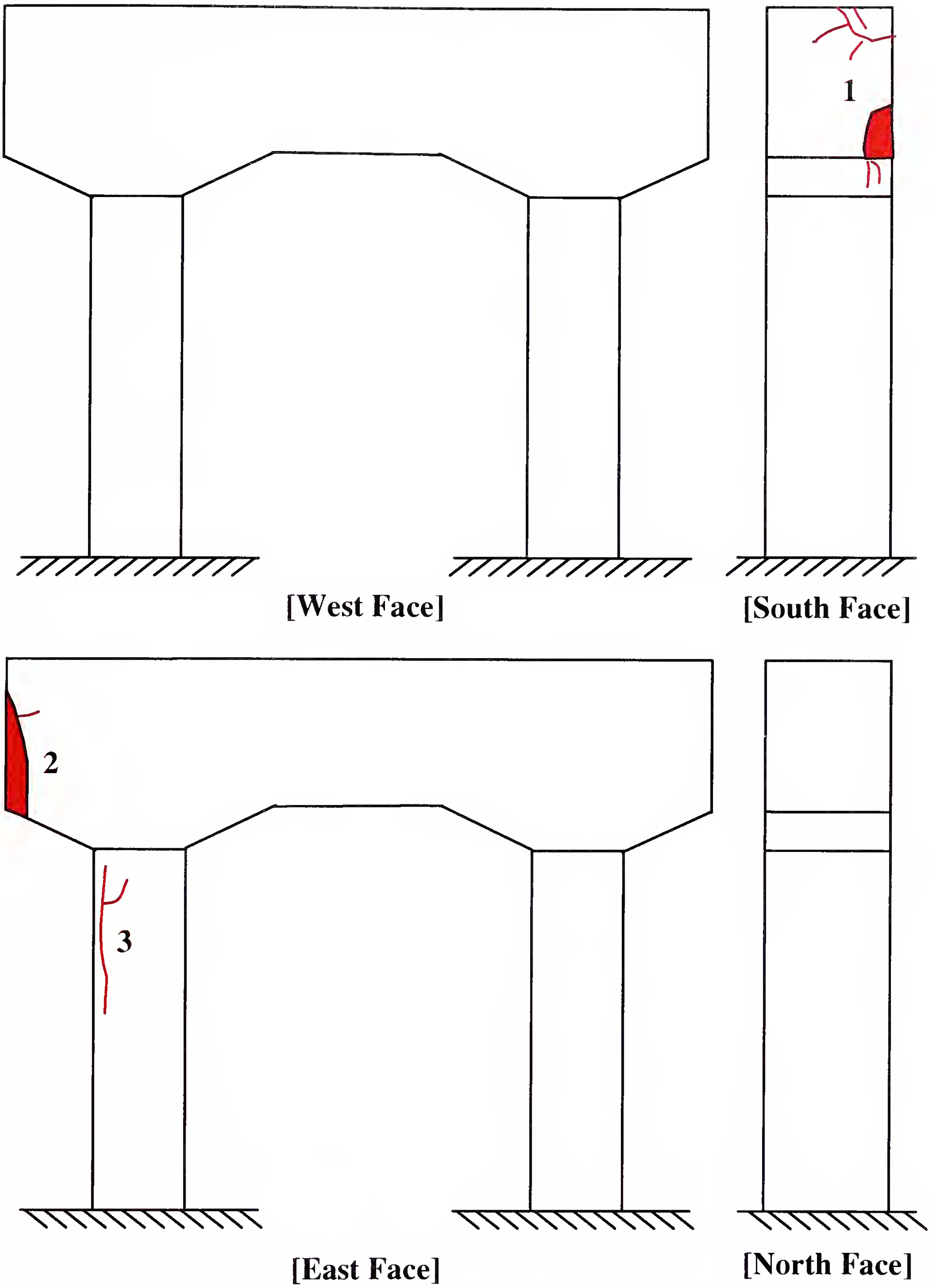
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage
	S. Col.	South	Small spall and a crack (1)	
	Cap	East	Small spall and a crack (2)	
	N. Col.	North	Small spall (3)	Test Performed: None

Figure 25A. Condition of Bent No. 26 (East Bound).



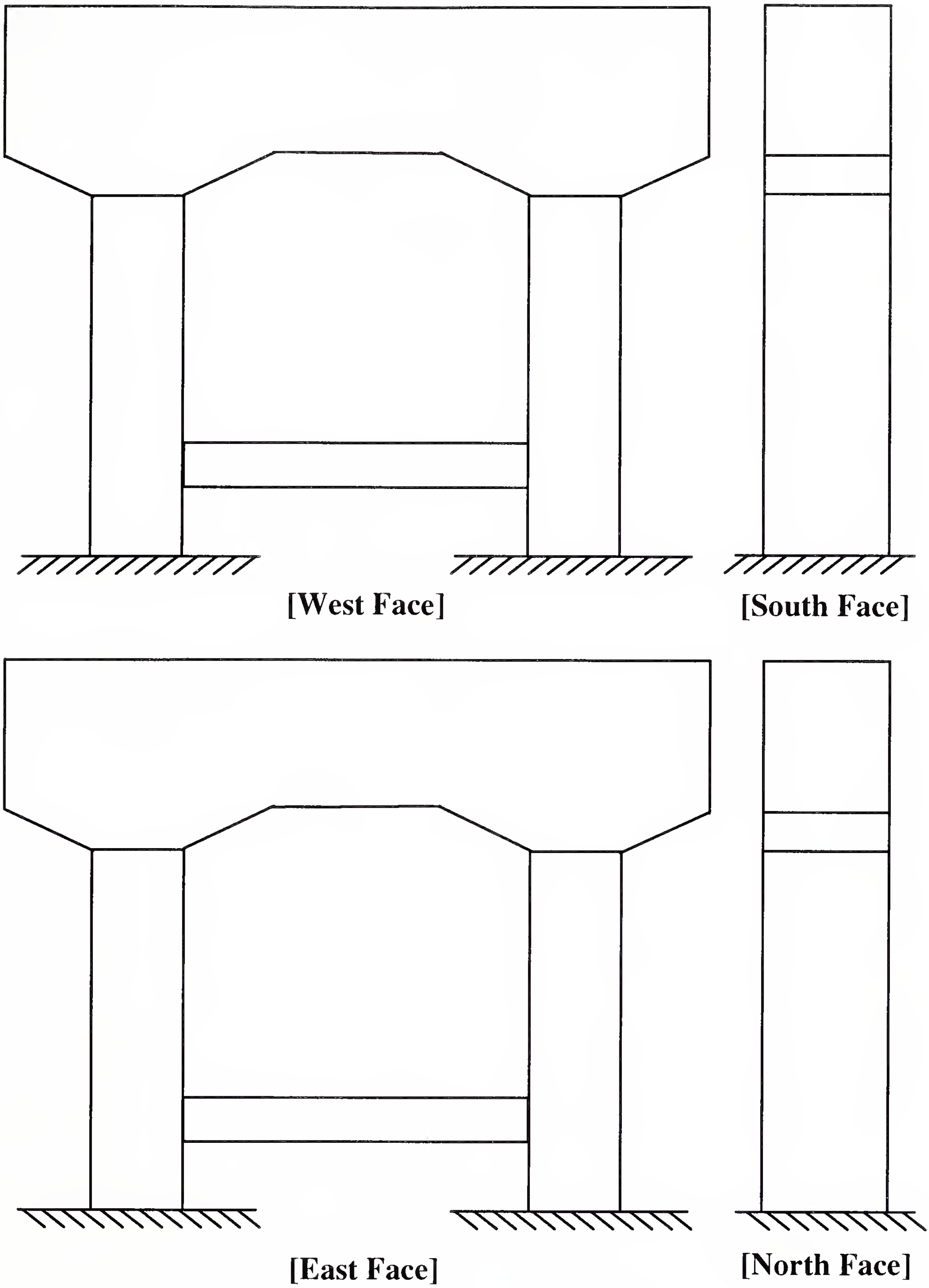
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Wet under beams 4-5 Test Performed: - CR1-10, & 15-20 - Carbonation Test at 3 locations - HCP measurement on 2 faces
	Cap	South	A crack (1)	
	S. Col.	South	Two spalls and three cracks (2)	
	S. Col.	West	Two spalls and a crack (3)	
	Cap	West	A spall, a delam. and a crack (4)	

Figure 26A. Condition of Bent No. 27 (East Bound).



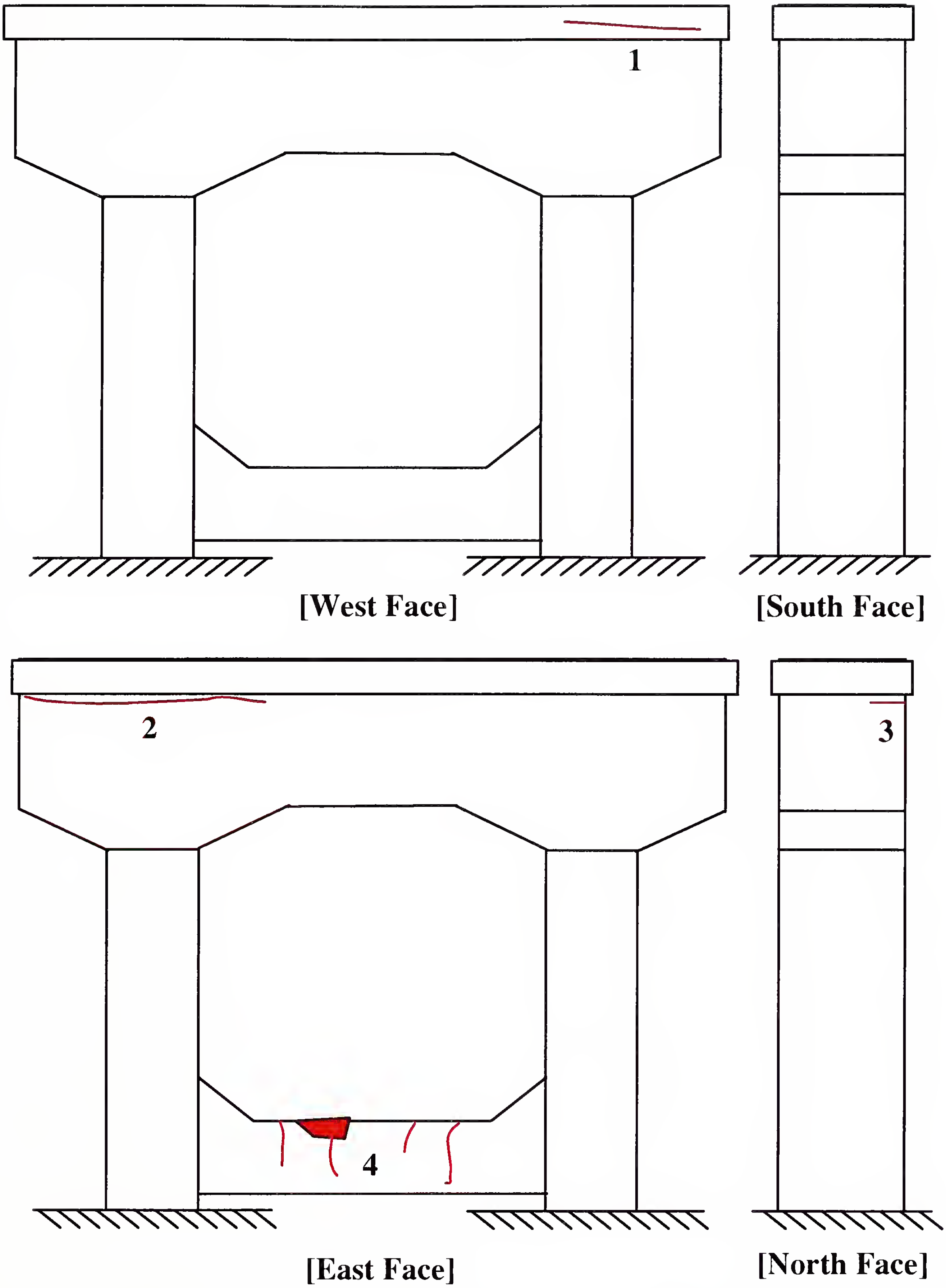
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but damp below beams 2-5 Test Performed: None
	S. Col.	South	Small spall and six cracks (1)	
	Cap	East	Small spall and a crack (2)	
	S. Col.	North	Two cracks (3)	

Figure 27A. Condition of Bent No. 28 (East Bound).



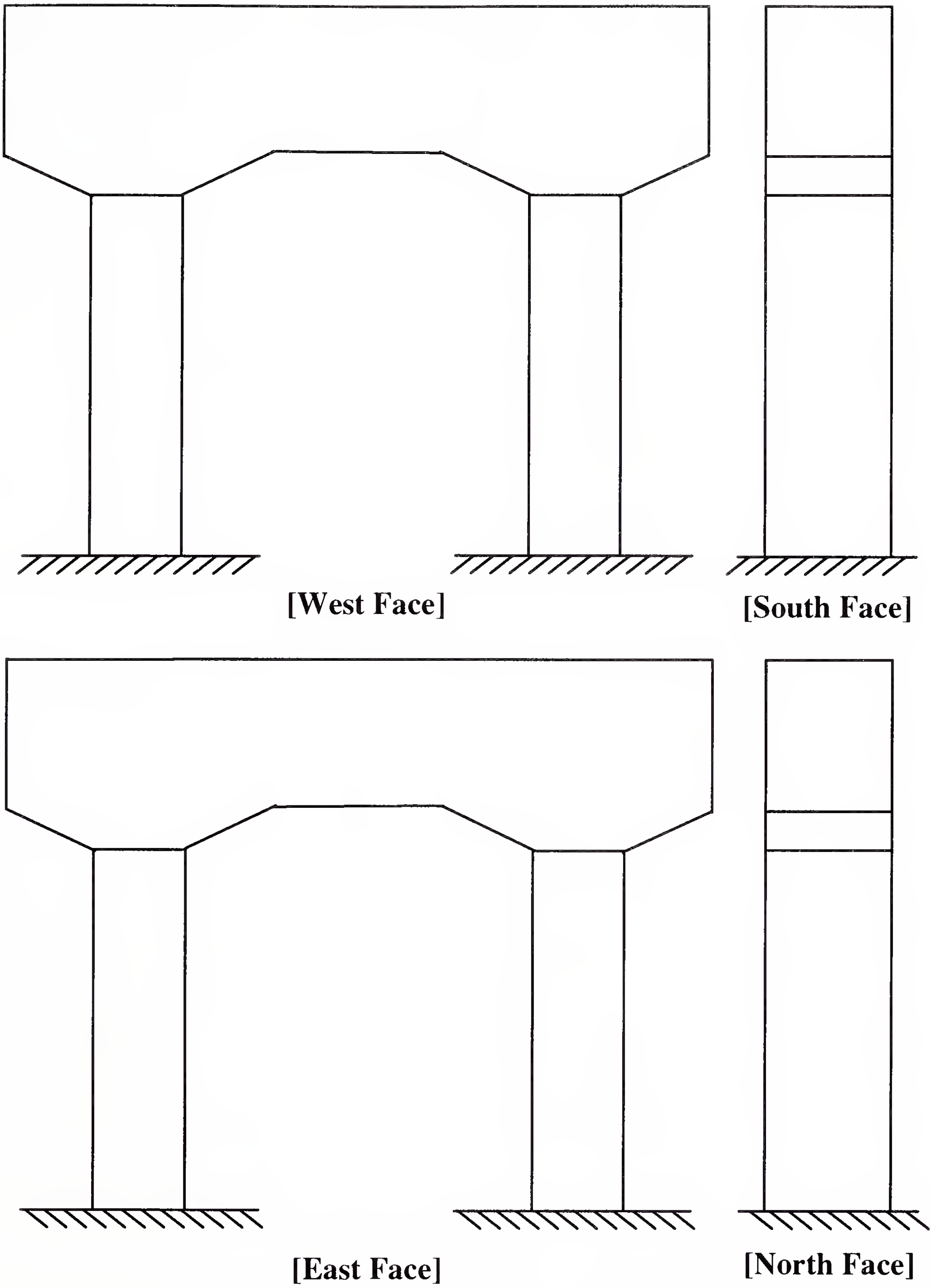
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage
		No Damage Observed		Test Performed: None

Figure 28A. Condition of Bent No. 29 (East Bound).



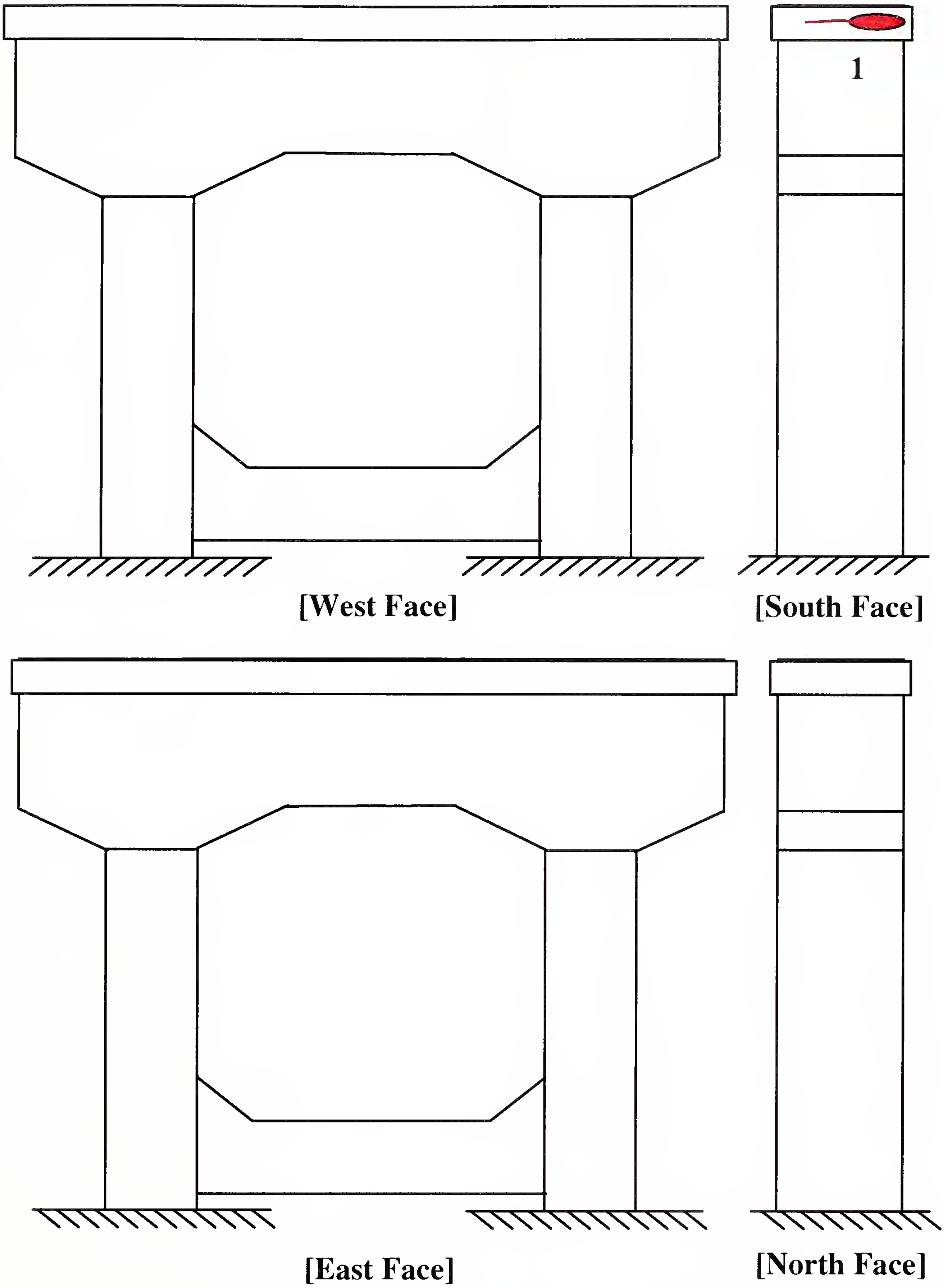
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage below beams 1-5 Test Performed: None
	Cap	West	A crack with stain (1)	
	Cap	East	A crack (2)	
	Cap	East	A crack (3)	
	Beam	East	A spall and four cracks (4)	

Figure 29A. Condition of Bent No. 30 (East Bound).



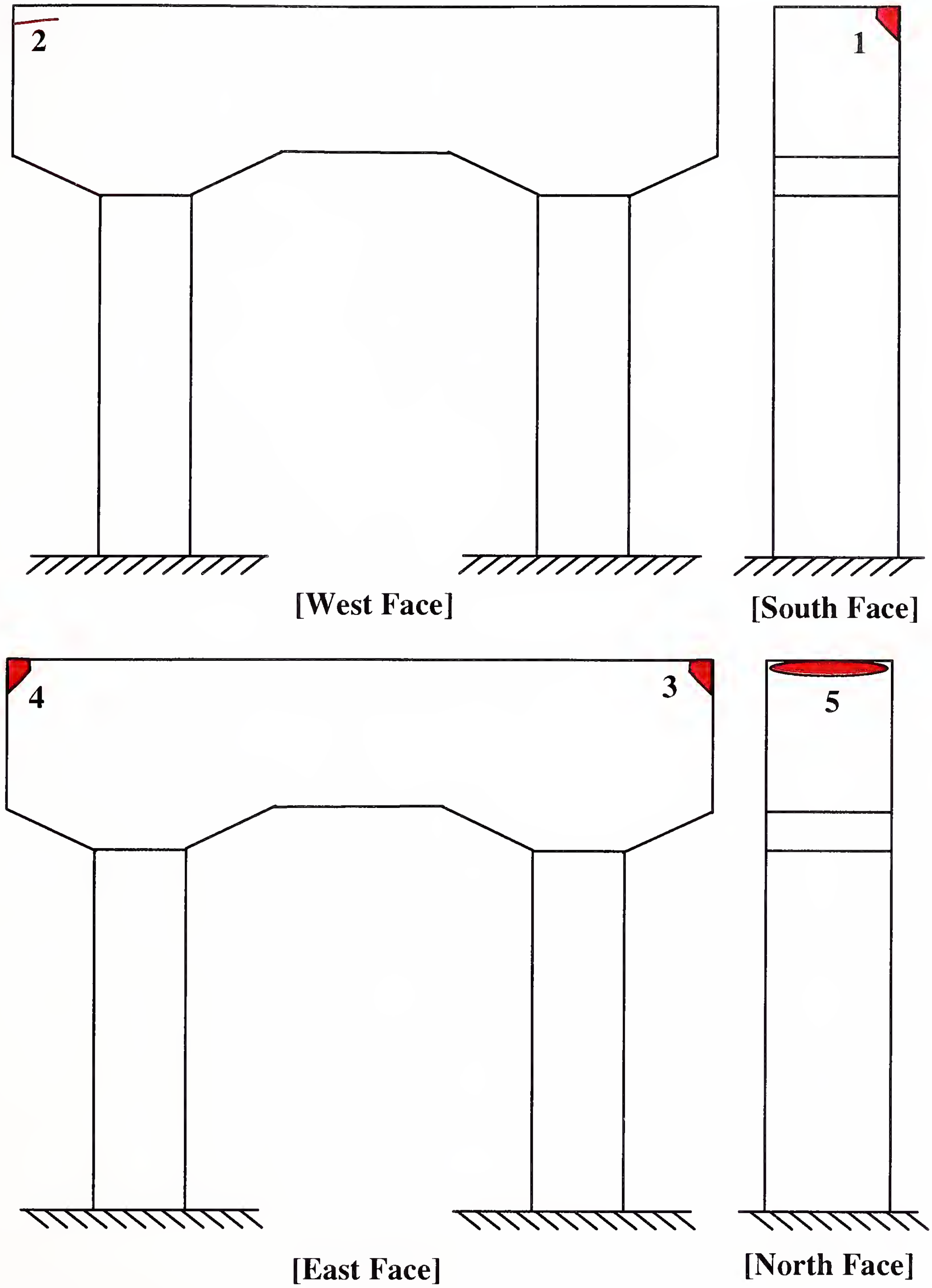
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage below beams 1-5 Test Performed: None
		No Damage Observed		

Figure 30A. Condition of Bent No. 31 (East Bound).



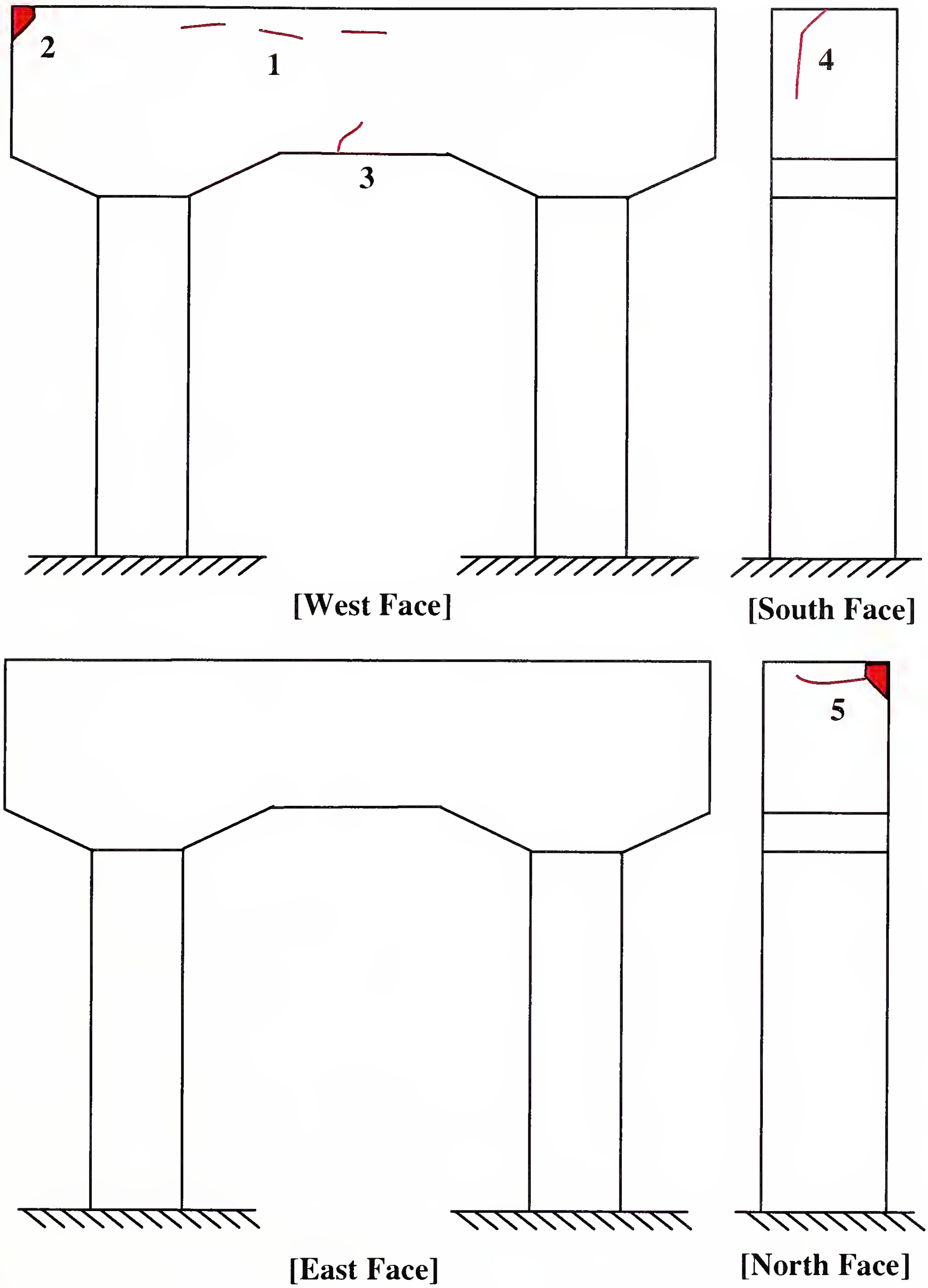
	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but moist
Damage	Cap	South	A spall and a crack (1)	
				Test Performed: None

Figure 31A. Condition of Bent No. 32 (East Bound).



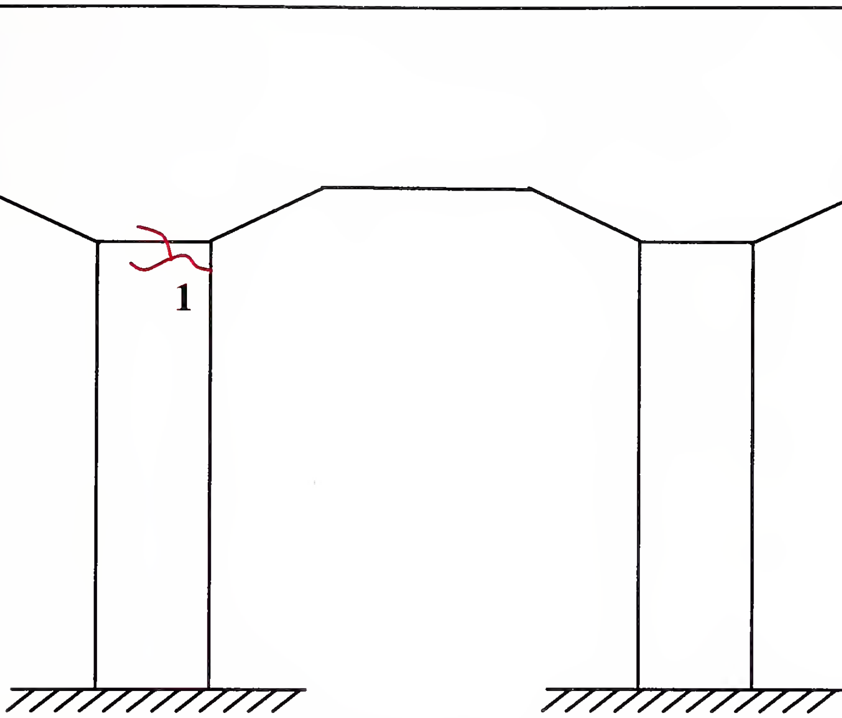
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage Test Performed: None
	Cap	South	Small spall (1)	
	Cap	West	A crack (2)	
	Cap	East	Small spall (3)	
	Cap	East	Small spall (4)	
	Cap	North	Spall exposing a rebar (5)	

Figure 32A. Condition of Bent No. 2 (West Bound).

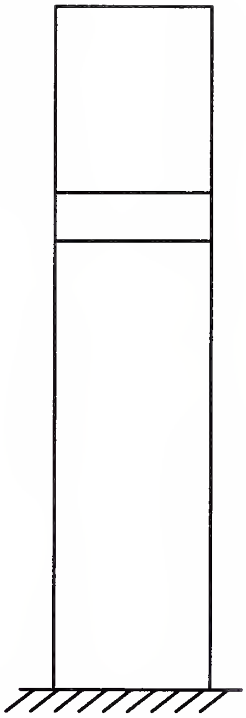


	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage in center and joint moist south end Test Performed: None
Damage	Cap	West	Three small cracks (1)	
	Cap	West	Small spall (2)	
	Cap	West	A crack extended to underside(3)	
	Cap	South	A crack (4)	
	Cap	North	Small spall and a crack (5)	

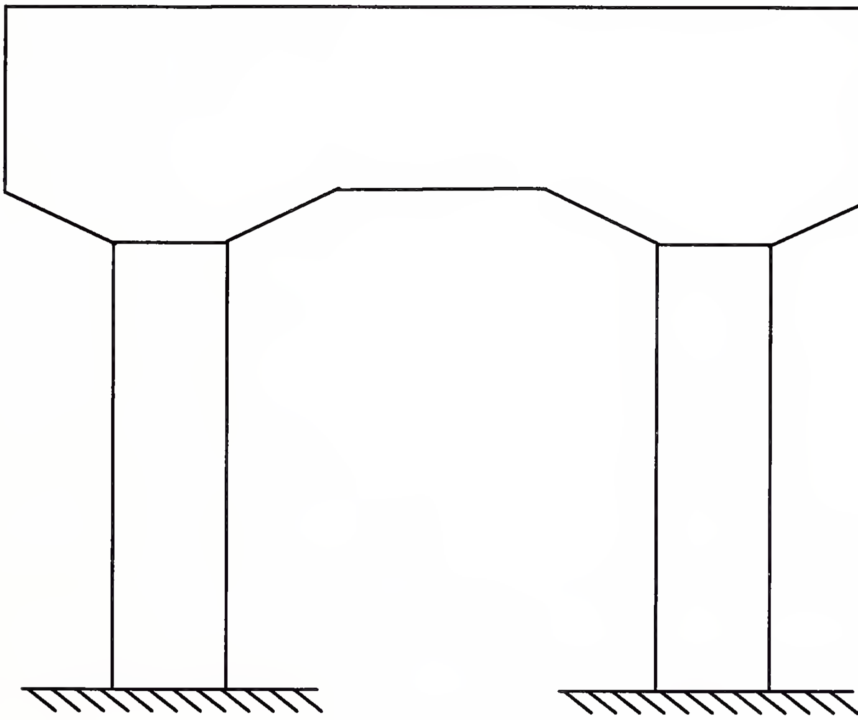
Figure 33A. Condition of Bent No. 3 (West Bound).



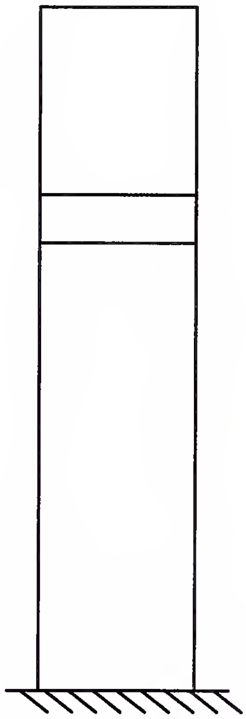
[West Face]



[South Face]



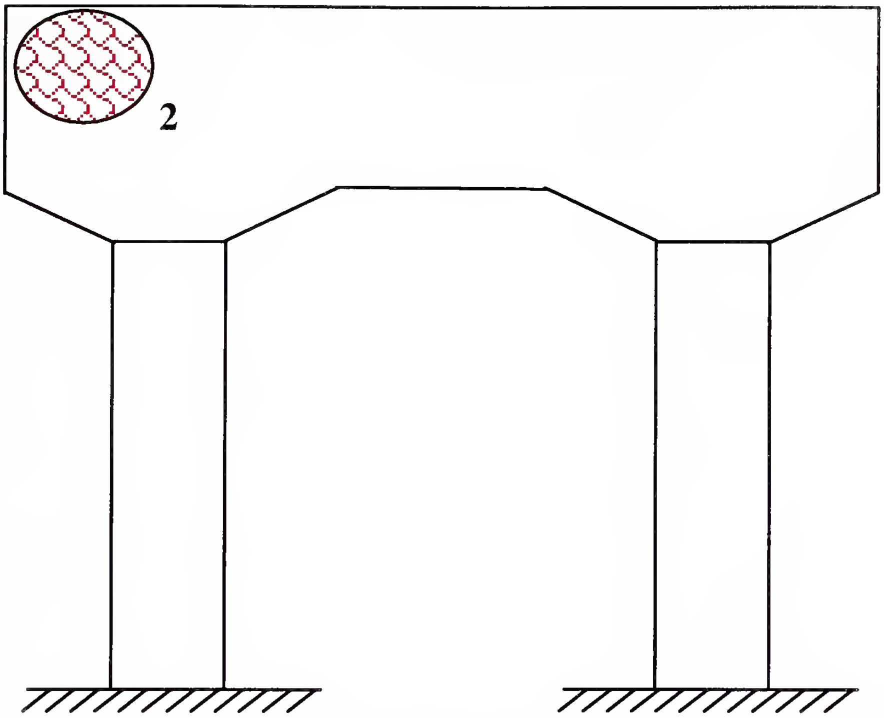
[East Face]



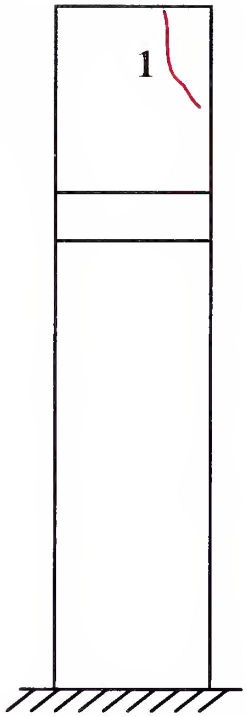
[North Face]

Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage Test Performed: None
	N. Col.	West	Two cracks (1)	

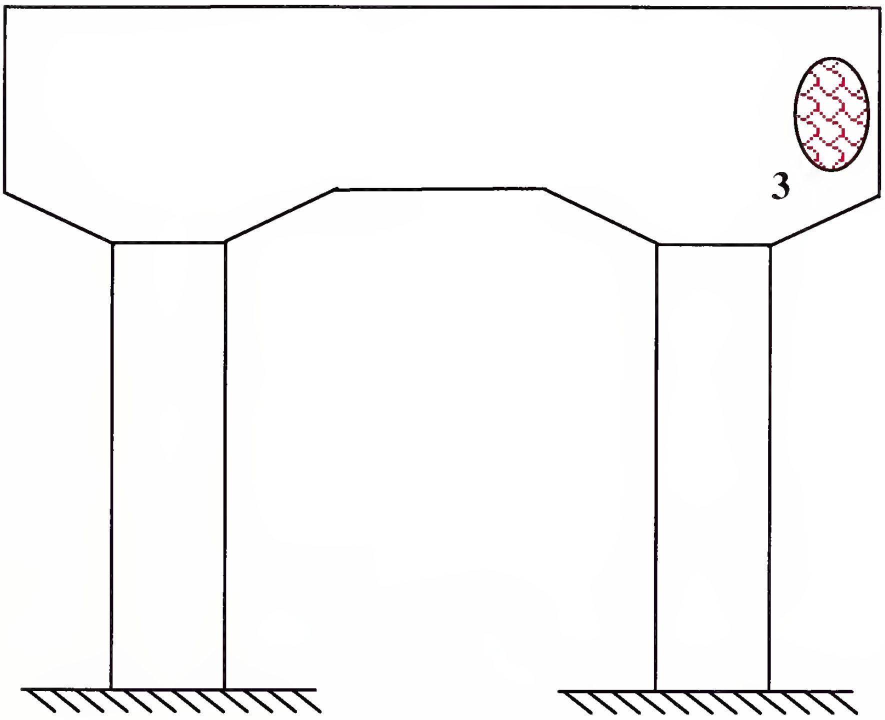
Figure 34A. Condition of Bent No. 4 (West Bound).



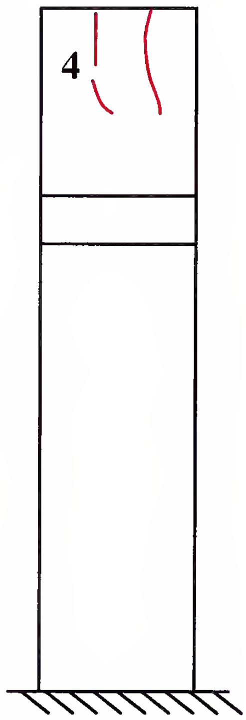
[West Face]



[South Face]



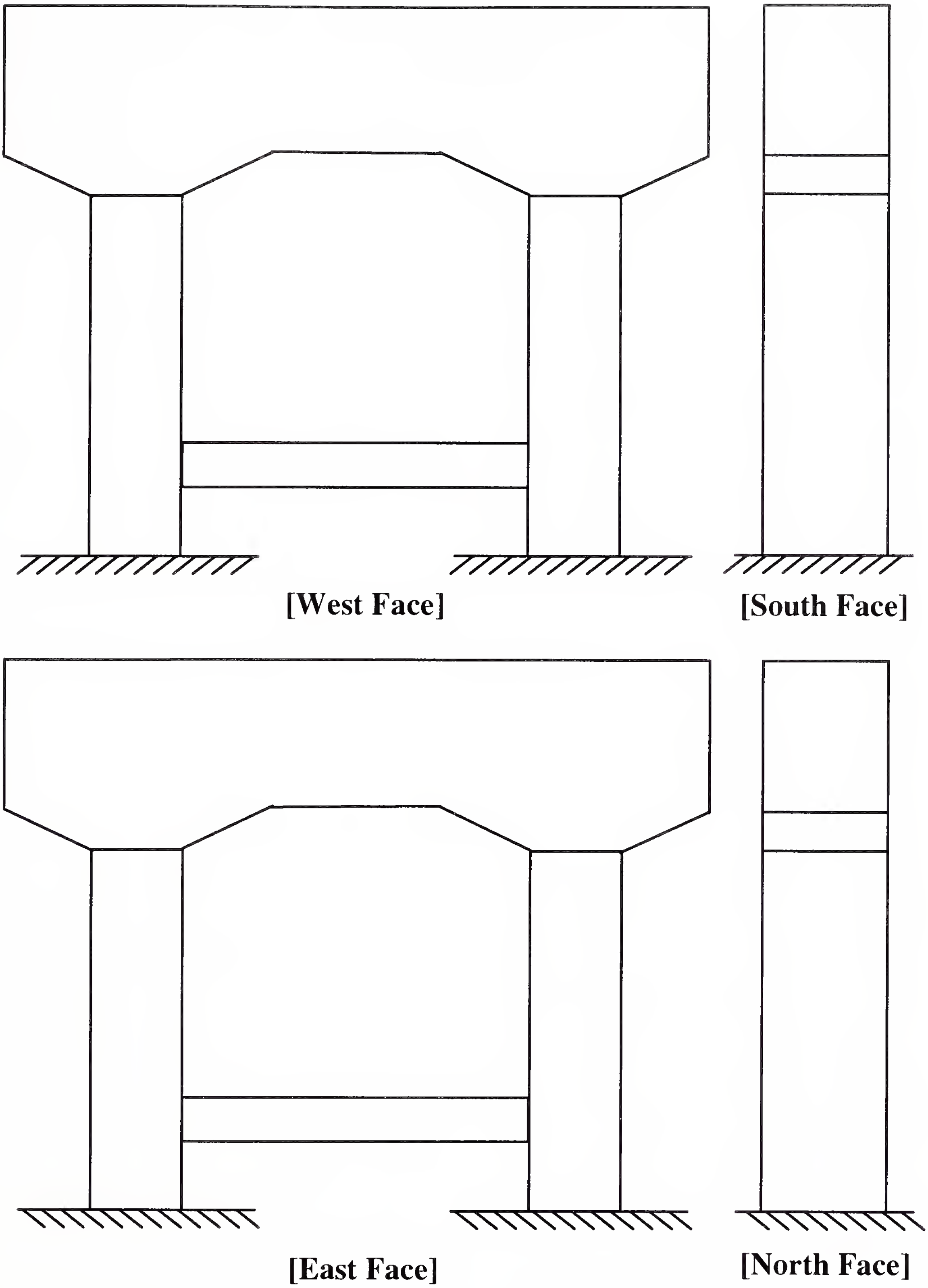
[East Face]



[North Face]

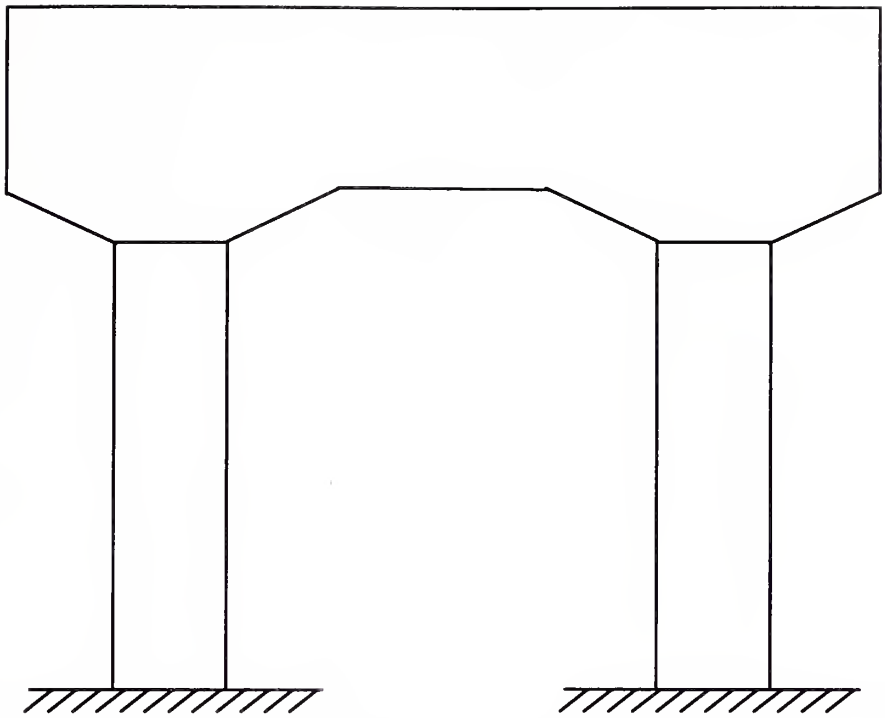
	Location	Face	Description of Damage (No.)	Leakage Condition: Moist below beams 1-2 Test Performed: None
Damage	Cap	South	A crack (1)	
	Cap	West	Pattern cracking (2)	
	Cap	East	Pattern cracking (3)	
	Cap	North	Three cracks (4)	

Figure 35A. Condition of Bent No. 5 (West Bound).

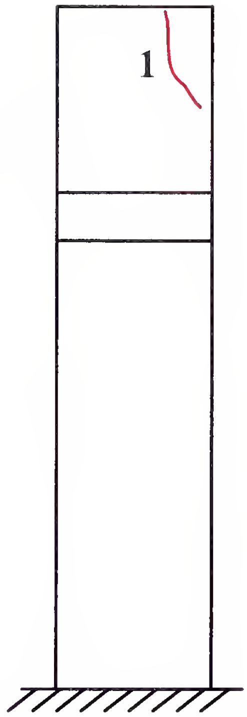


Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage
		No Damage Observed		Test Performed: None

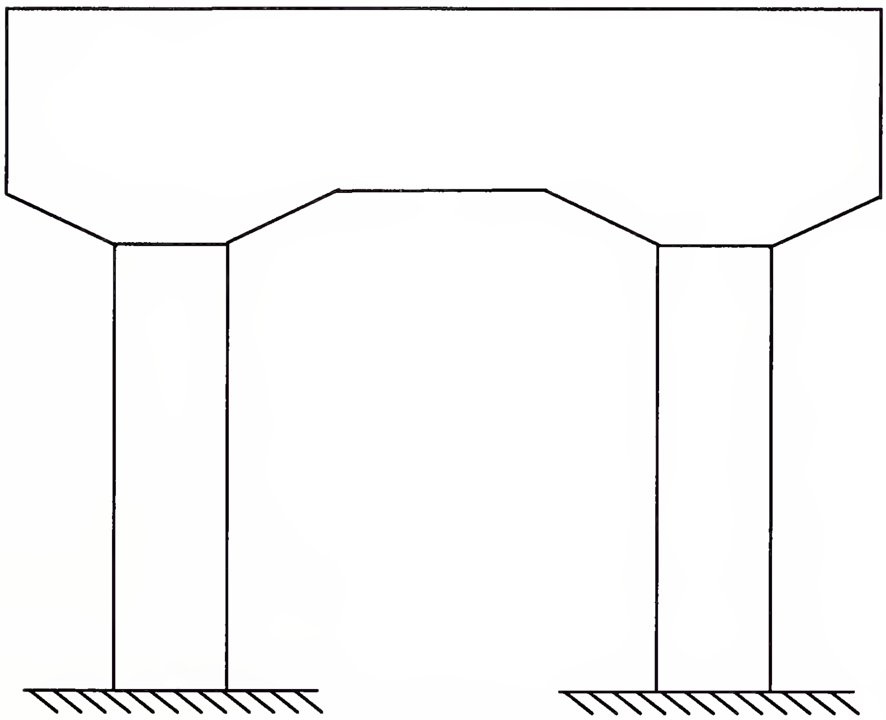
Figure 36A. Condition of Bent No. 6 (West Bound).



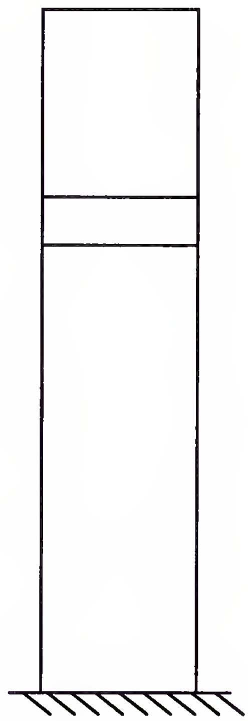
[West Face]



[South Face]



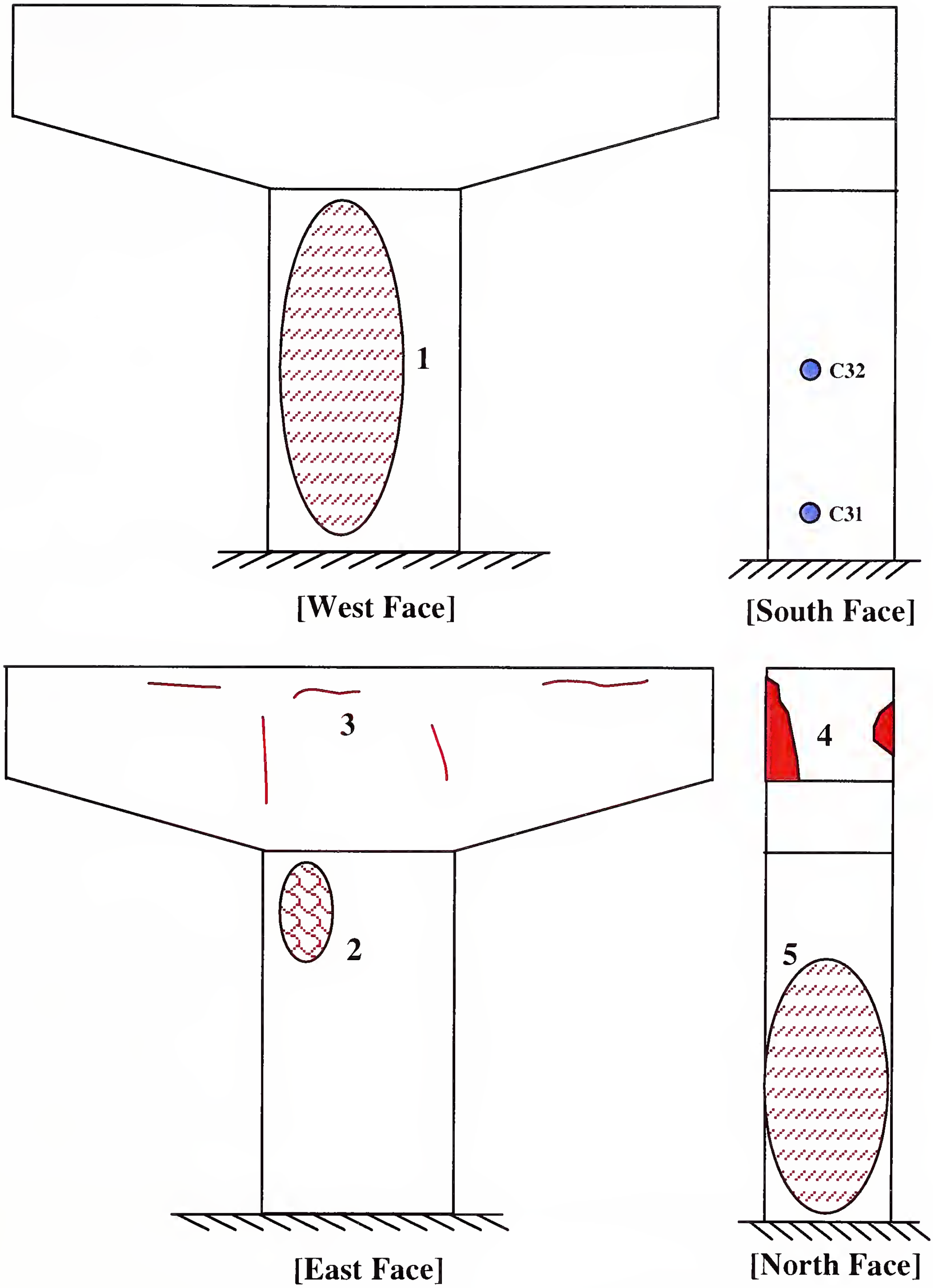
[East Face]



[North Face]

Damage	Location	Face	Description of Damage (No.)	
	Cap	South	A crack (1)	Leakage Condition: No Leakage
				Test Performed: None

Figure 37A. Condition of Bent No. 7 (West Bound).



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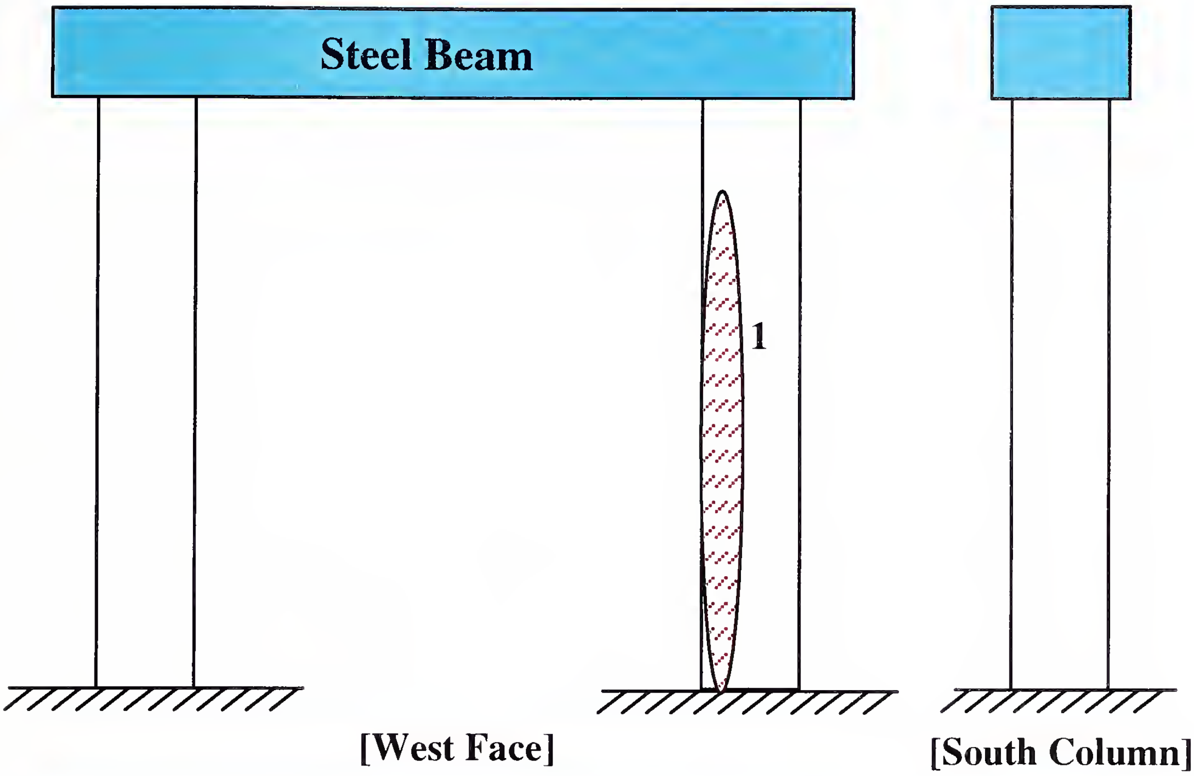
<tr><td rowspan="6">Damage</td><td>Location</td><td>Face</td><td>Description of Damage (No.)</td><td rowspan="6">Leakage Condition:
Active leakage below beams 1-2, 2-3, 3-4

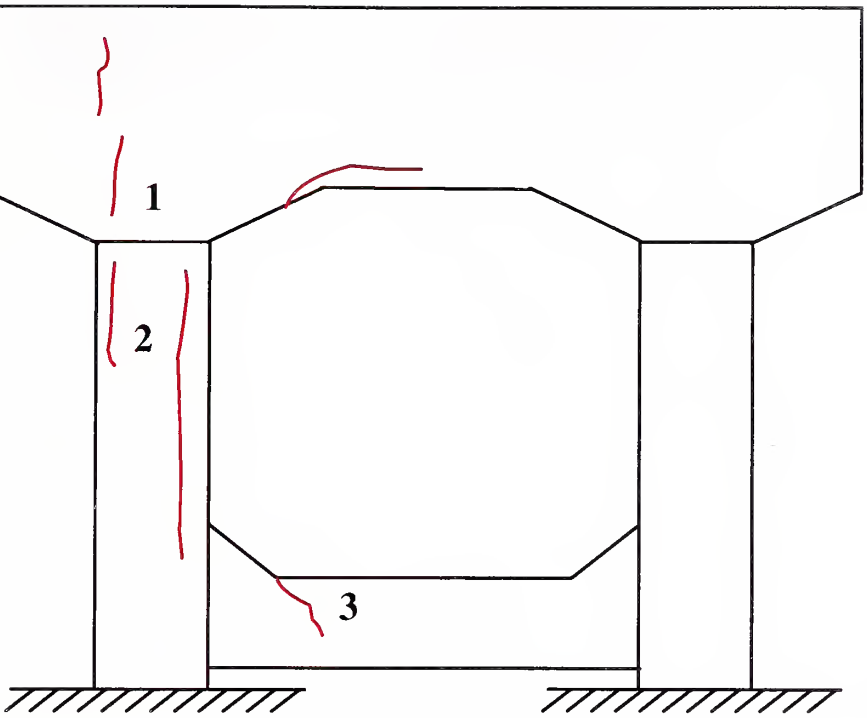
Test Performed:
- Cores C31 and C32</td></tr>
<tr><td>Column</td><td>West</td><td>Multiple cracks (1)</td></tr>
<tr><td>Column</td><td>East</td><td>Pattern cracking (2)</td></tr>
<tr><td>Column</td><td>East</td><td>Five cracks (3)</td></tr>
<tr><td>Column</td><td>North</td><td>Two spalls (4)</td></tr>
<tr><td>Column</td><td>North</td><td>Multiple cracks (5)</td></tr>
</table>

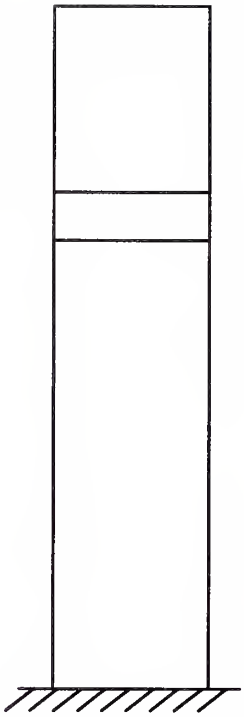
Figure 38A. Condition of Bent No. 8 (West Bound).



Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No deck above and exposed Test Performed: None
	Column	Circular	Multiple cracks on NW and	
			W sides (1): Photo taken	

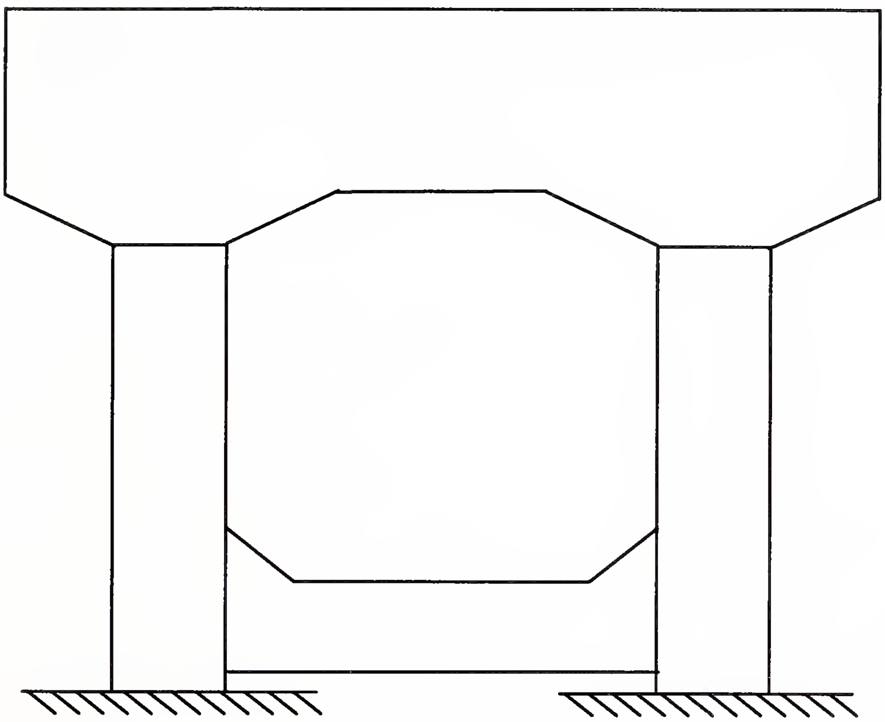
Figure 39A. Condition of Bent No. 9 (West Bound).

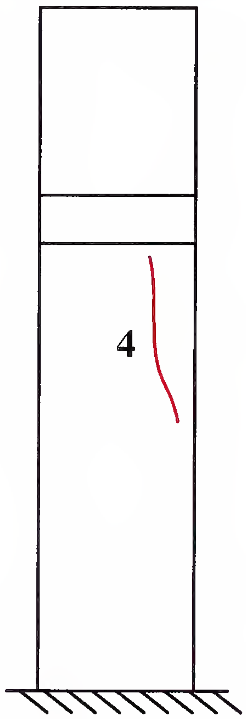




[West Face]

[South Face]



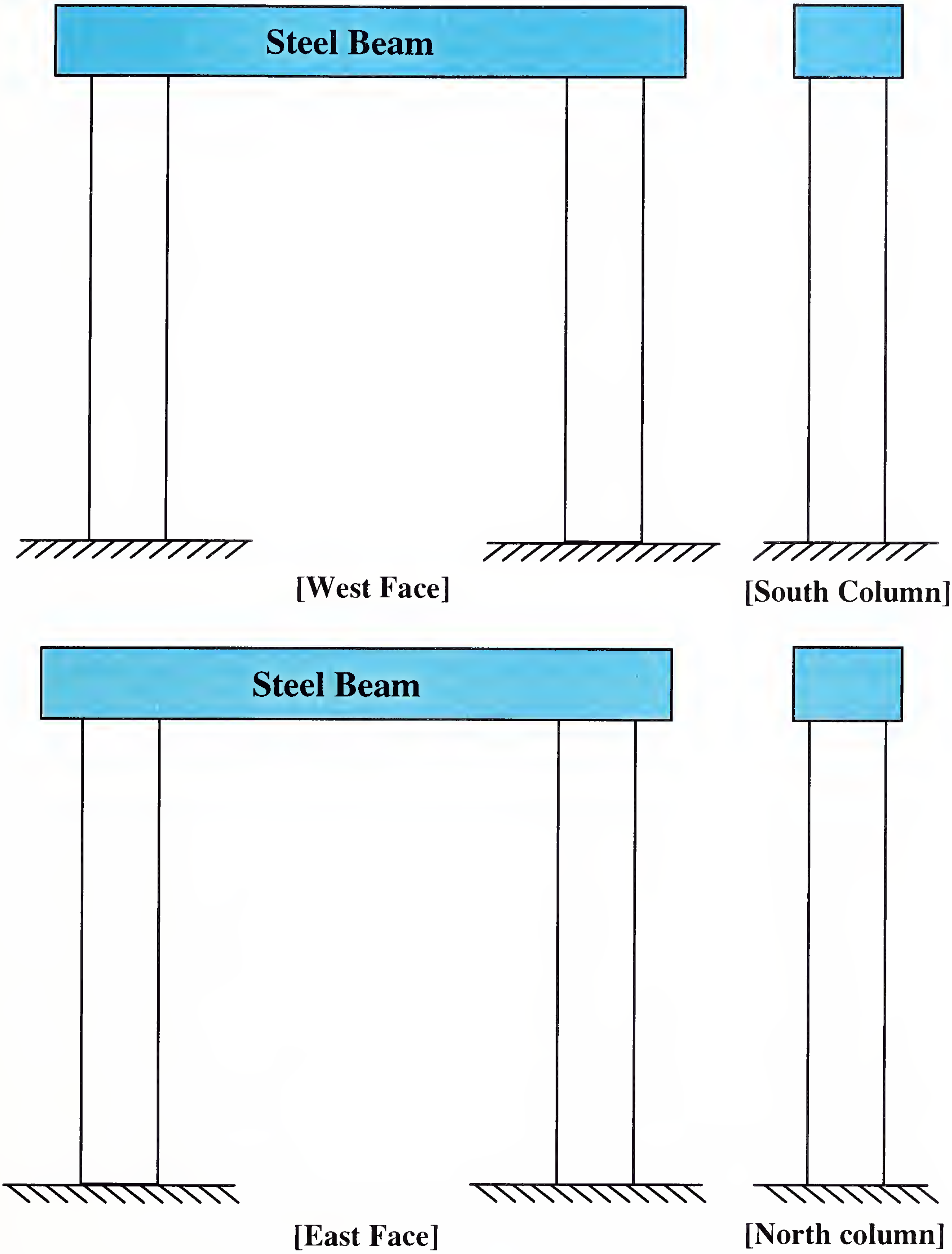


[East Face]

[North Face]

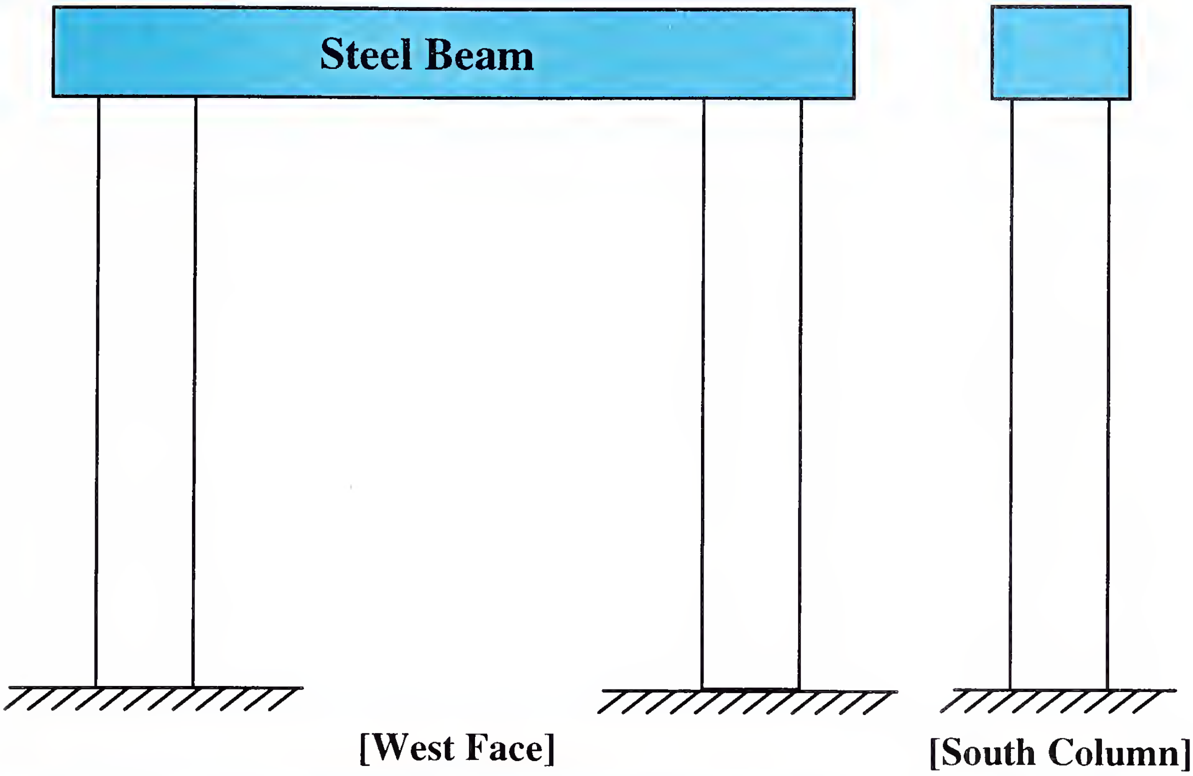
	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage below beams 1-2 and moist below beams 2-3, 3-4 Test Performed: None
Damage	Cap	West	Three cracks (1)	
	N. Col.	West	Two cracks (2)	
	Beam	West	A crack (3)	
	N. Col.	North	A crack (4)	

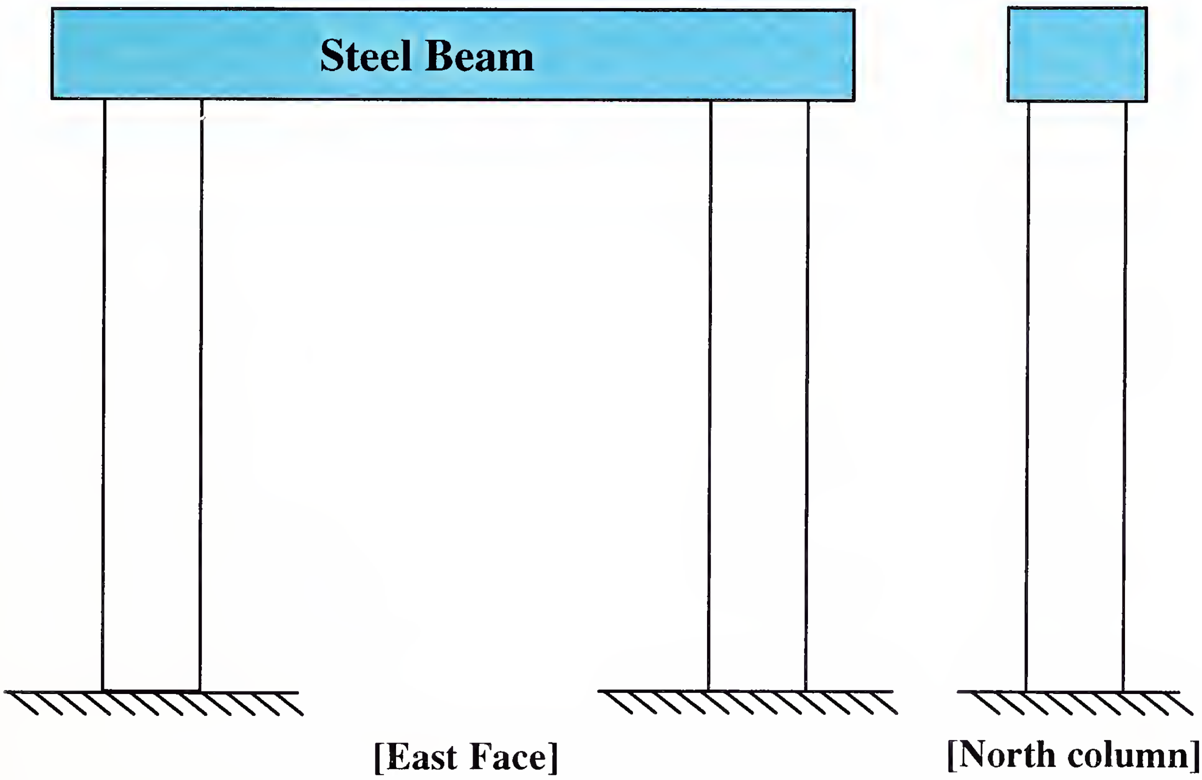
Figure 40A. Condition of Bent No. 10 (West Bound).



Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No deck above and exposed Test Performed: None
		No Damage Observed		

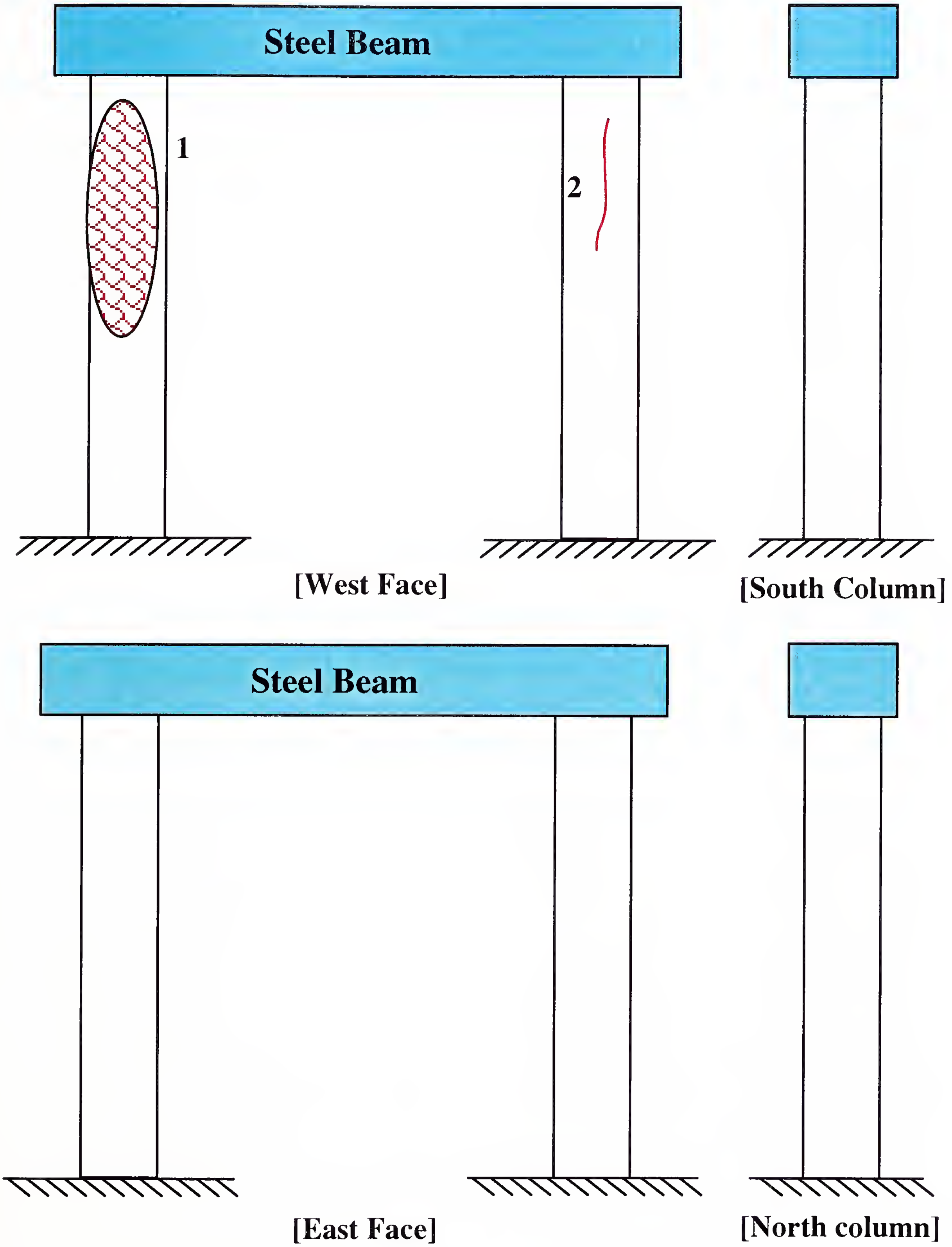
Figure 41A. Condition of Bent No. 11 (West Bound).





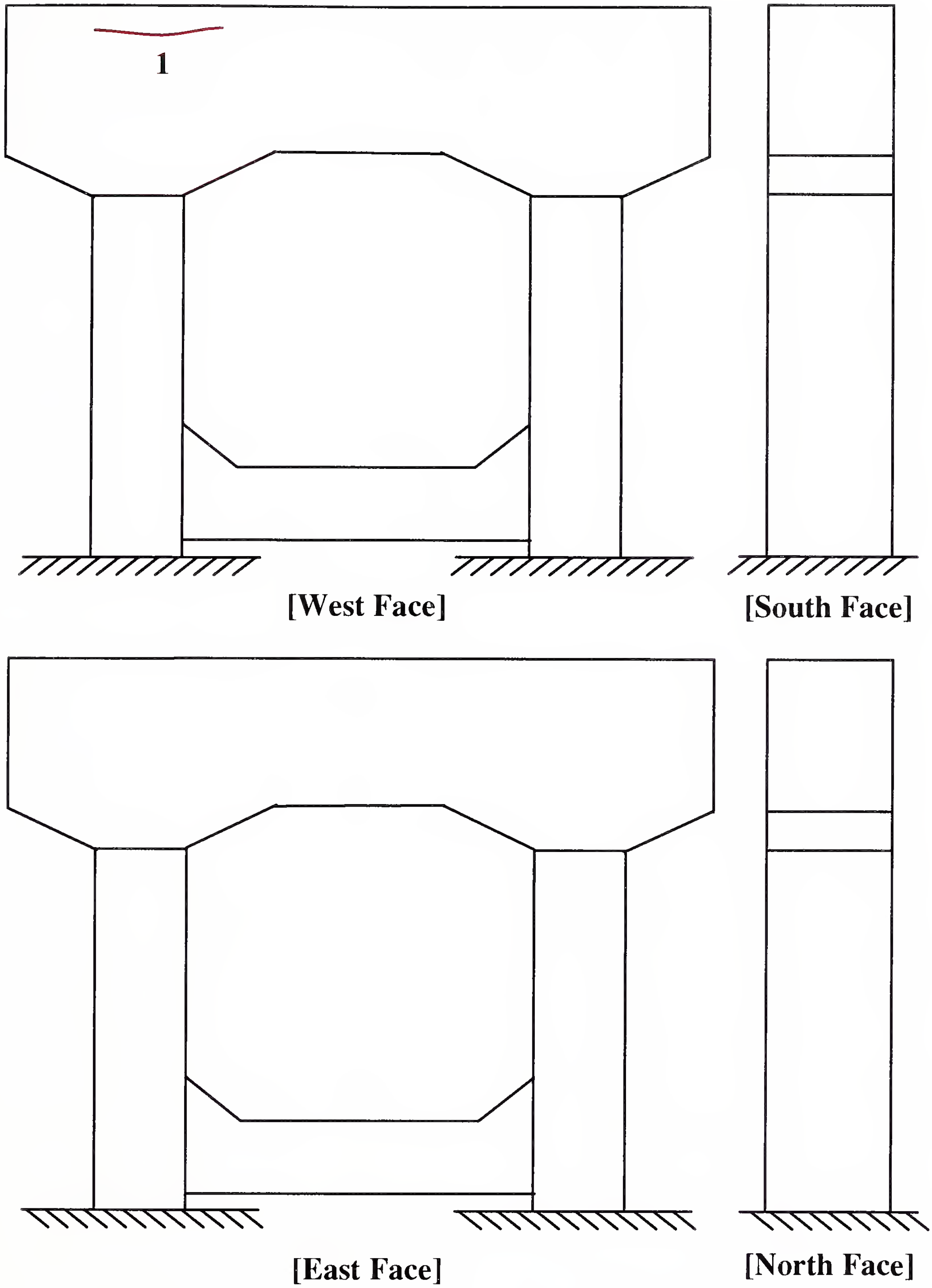
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No deck above and exposed Test Performed: None
	No Damage Observed			

Figure 42A. Condition of Bent No. 12 (West Bound).



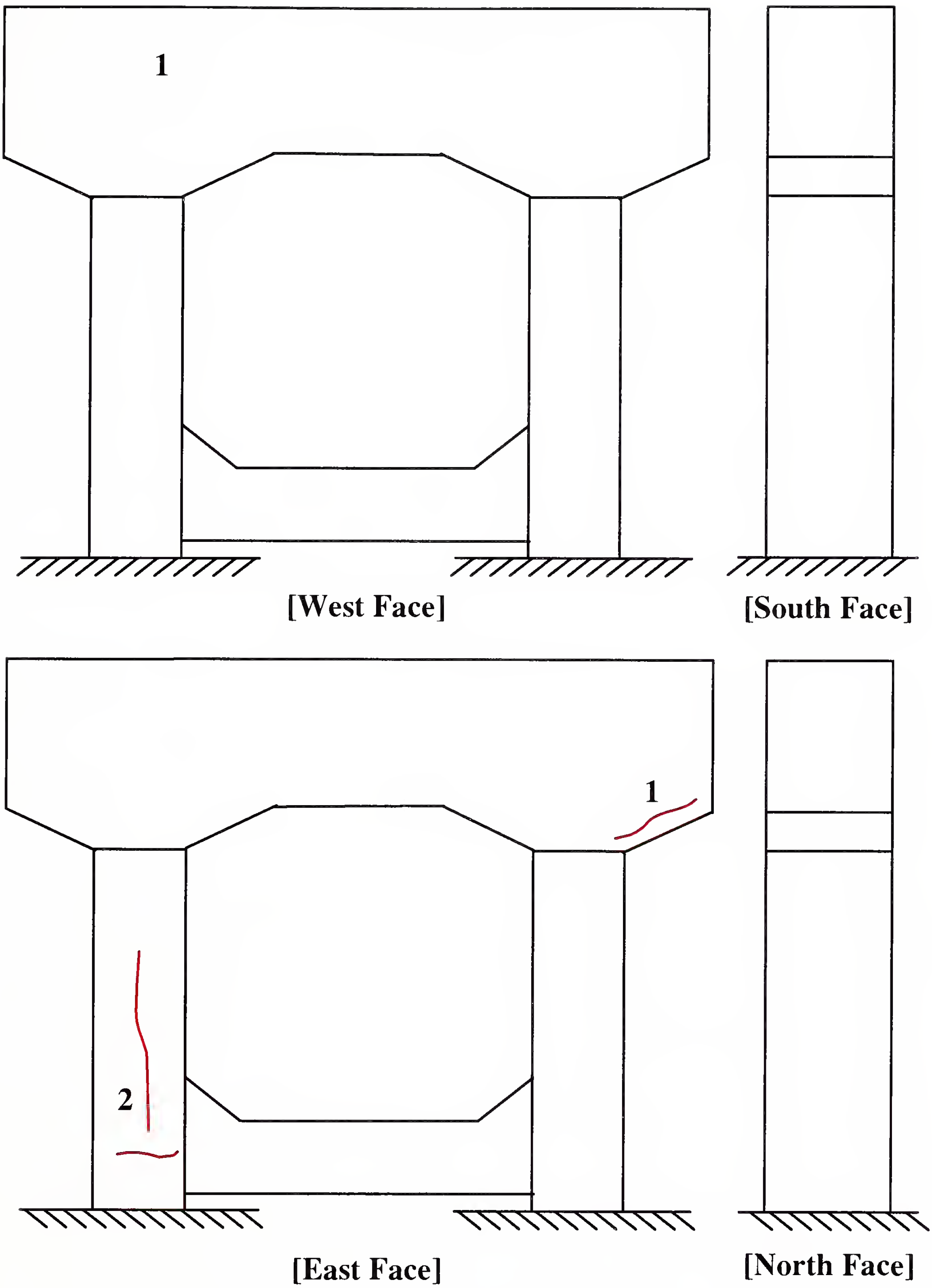
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No deck above and exposed Test Performed: None
	Column	West	Pattern cracking (1)	
	Column	West	A crack (2)	

Figure 43A. Condition of Bent No. 13 (West Bound).



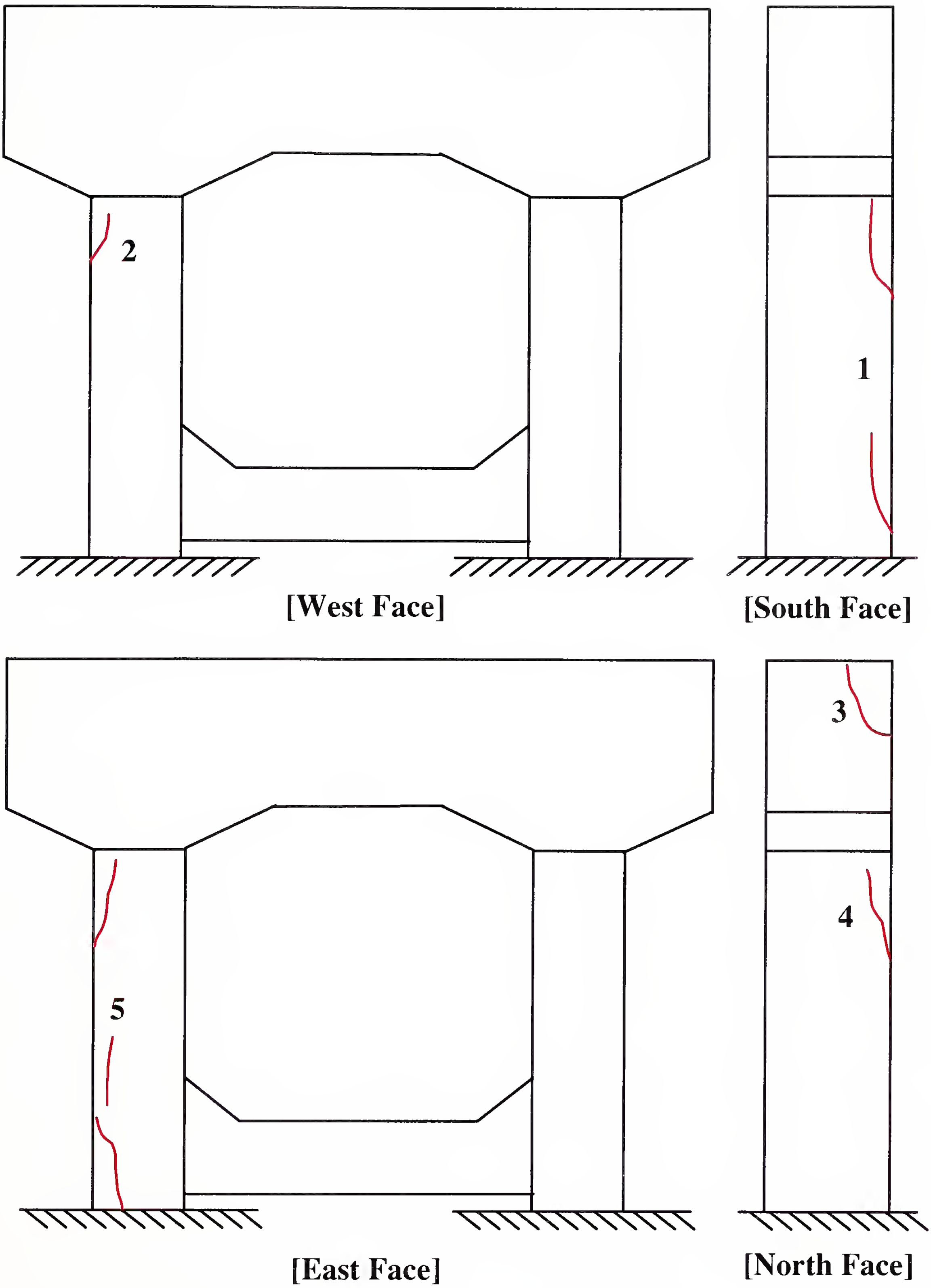
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage Test Performed: None
	Cap	West	A crack (1)	

Figure 44A. Condition of Bent No. 14 (West Bound).



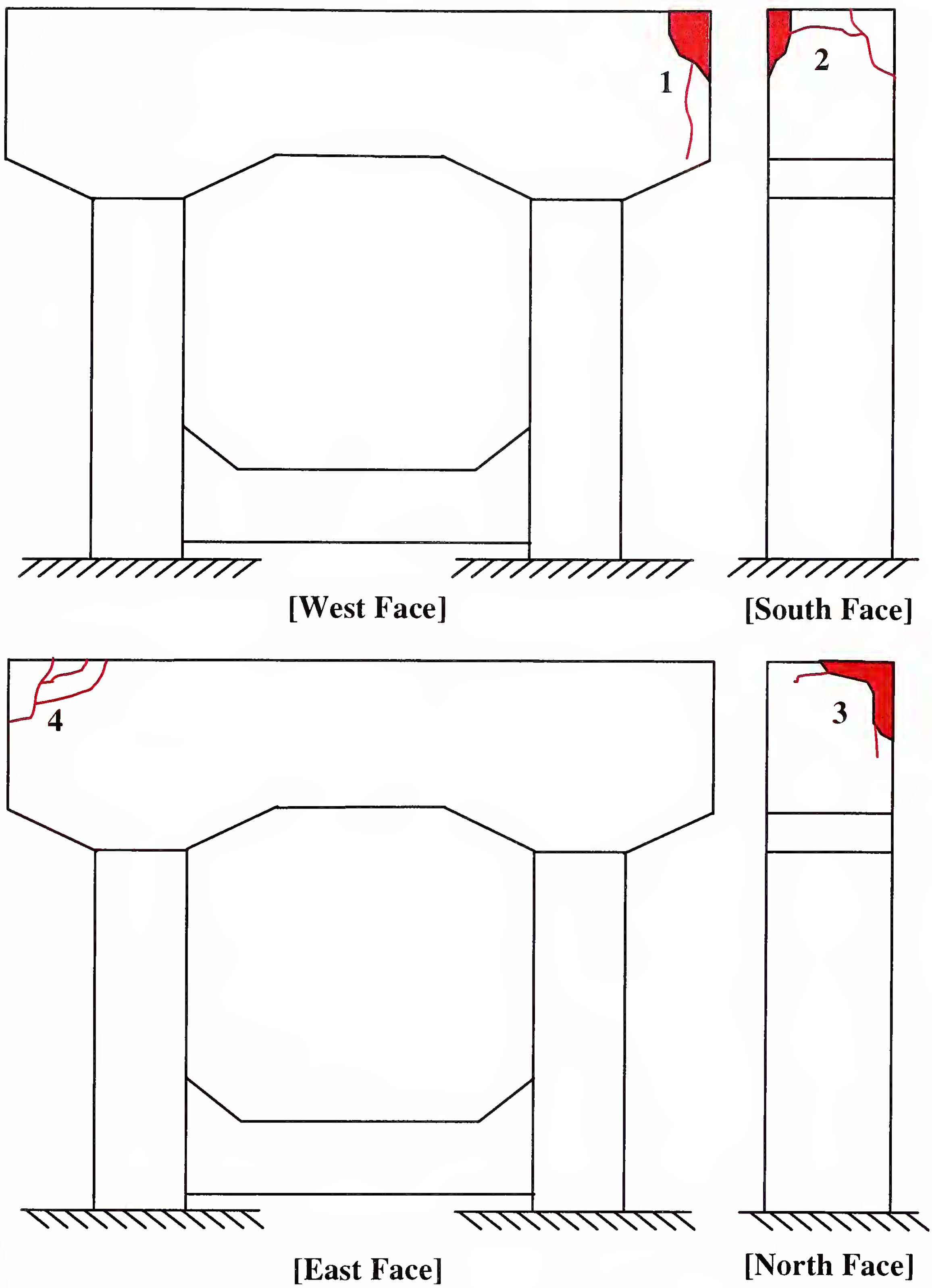
	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage below beams 3-4, 4-5 and moist below beams 2-3 Test Performed: None
Damage	Cap	East	A crack along the edge (1)	
	S. Col.	East	Two cracks (2)	

Figure 45A. Condition of Bent No. 15 (West Bound).



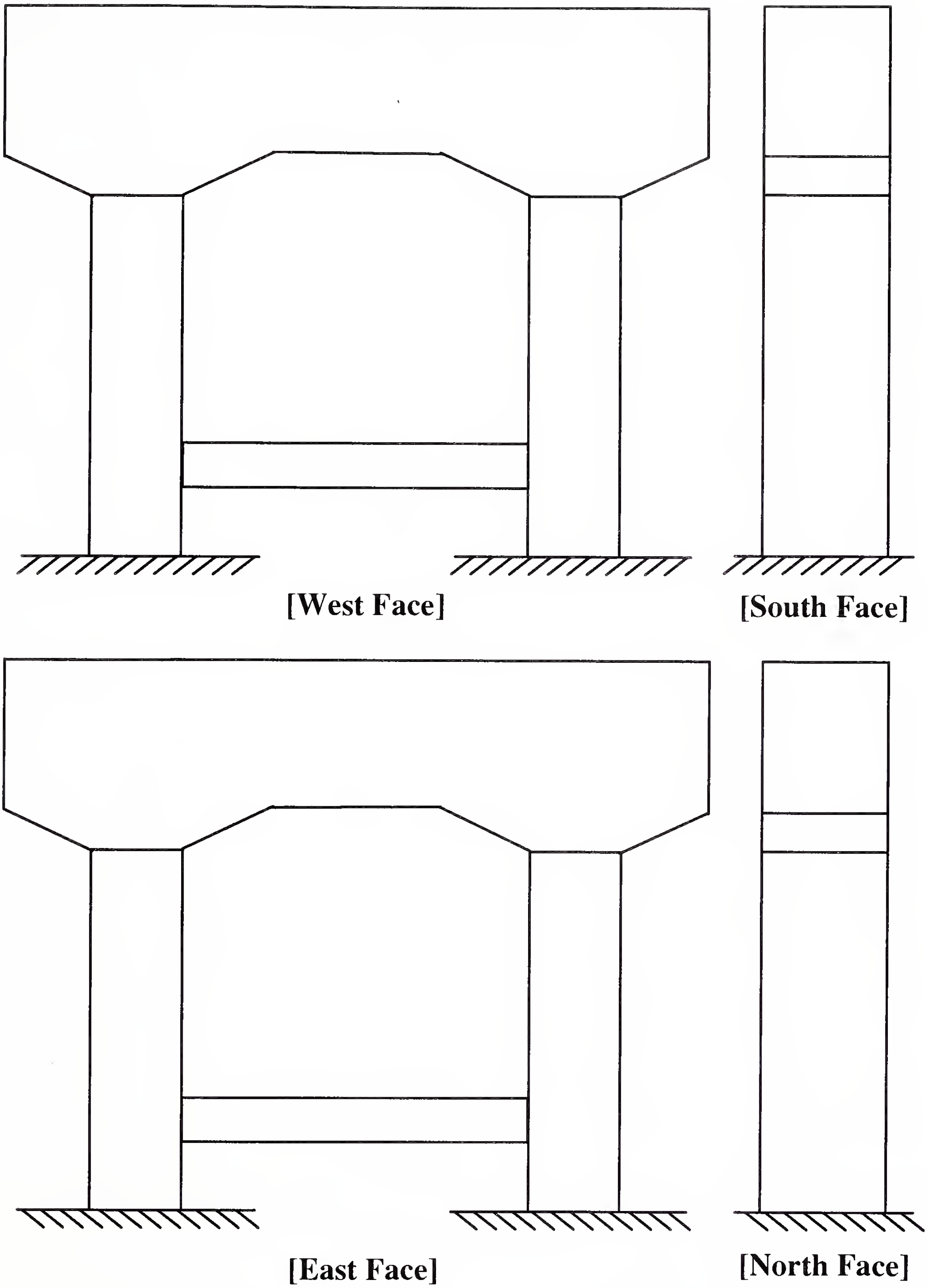
	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage
Damage	S. Col.	South	Two cracks (1)	
	N. Col.	West	A crack (2)	
	Cap	West	A crack (3)	Test Performed: None
	N. Col.	North	A crack (4)	
	S. Col.	East	Three cracks (5)	

Figure 46A. Condition of Bent No. 16 (West Bound).



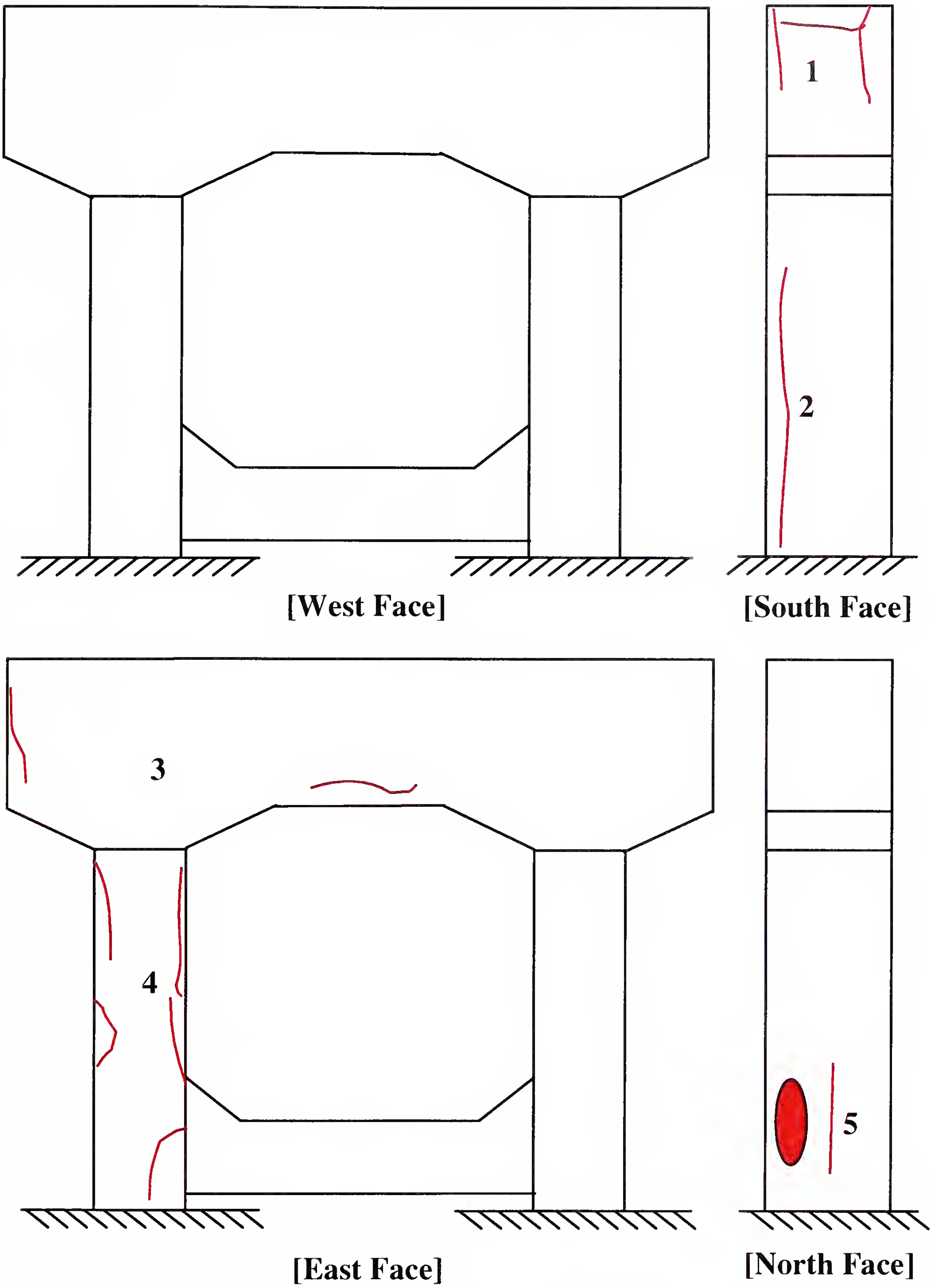
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but moist
	Cap	West	Spall and a crack (1)	
	Cap	South	Spall and two cracks (2)	
	Cap	North	Spall and two cracks (3)	Test Performed: None
	Cap	East	Three cracks (4)	

Figure 47A. Condition of Bent No. 17 (West Bound).



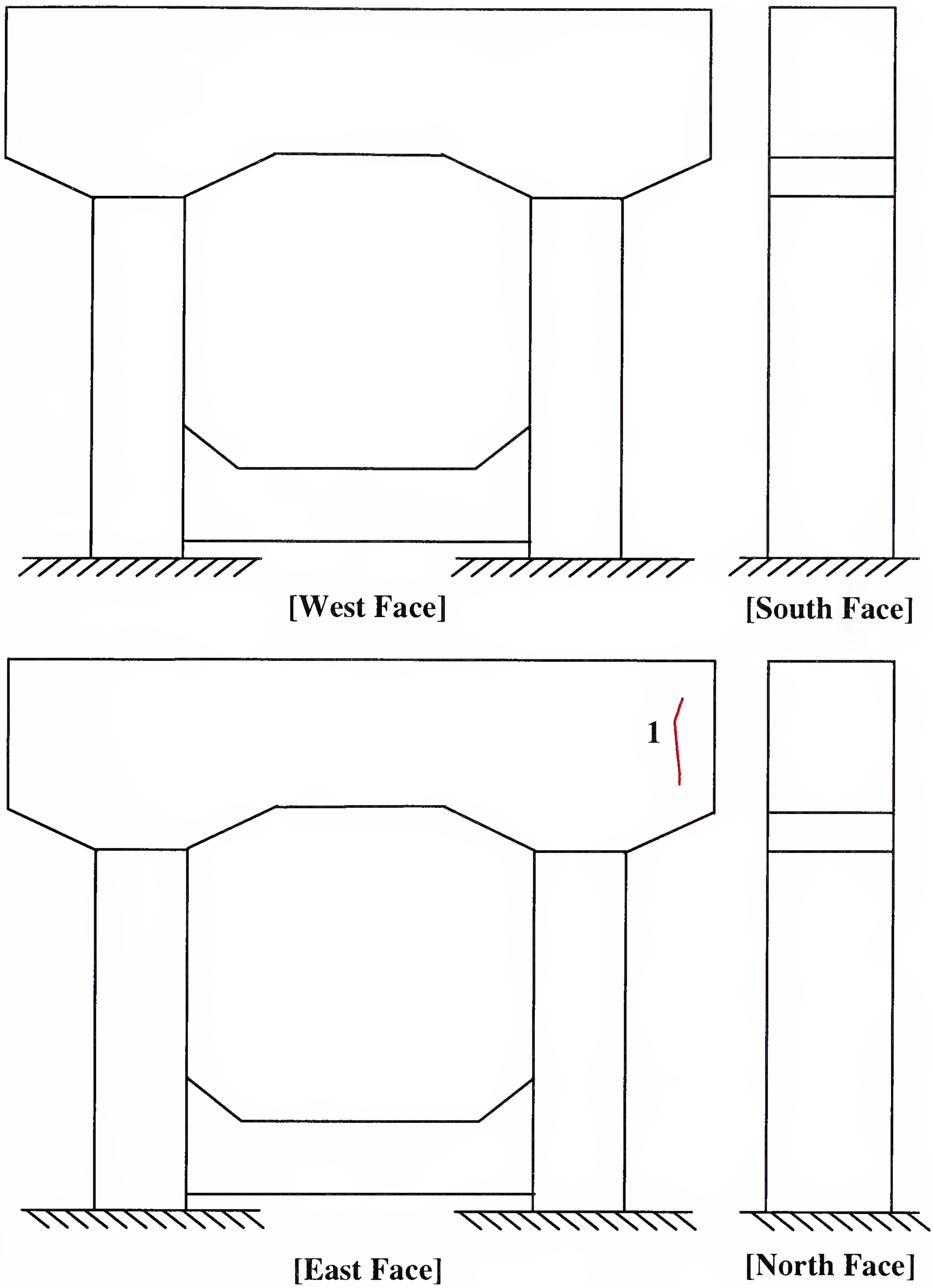
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage
		No Damage Observed		Test Performed: None

Figure 48A. Condition of Bent No. 18 (West Bound).



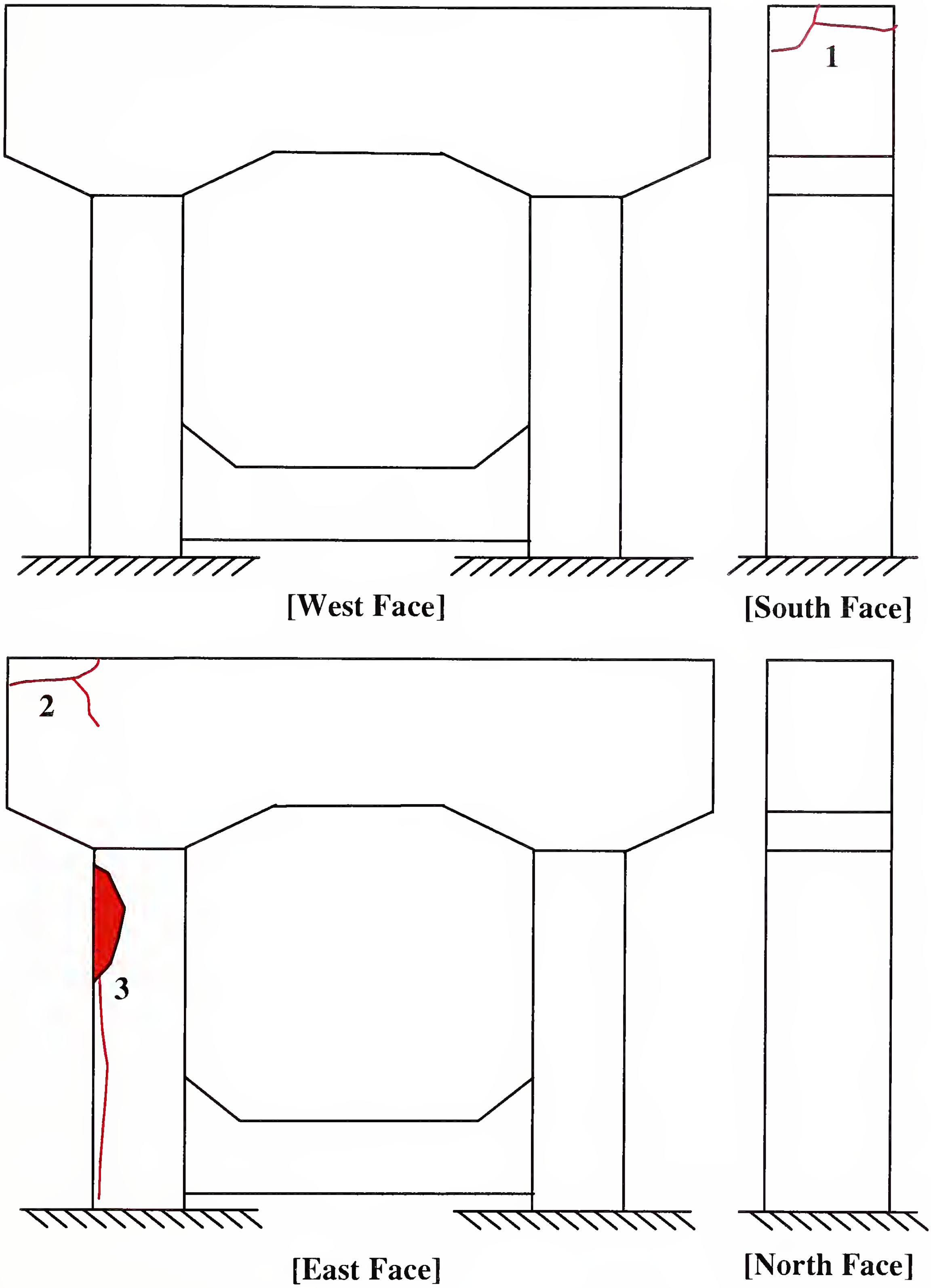
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Very active leakage below beams 4-5 and wet below beams 3-4 Test Performed: None
	Cap	South	Three cracks (1)	
	S. Col.	South	A crack (2)	
	Cap	East	Two cracks (3)	
	S. Col.	East	Five cracks(4)	
	N. Col.	North	Spall and a crack (5)	

Figure 49A. Condition of Bent No. 19 (West Bound).



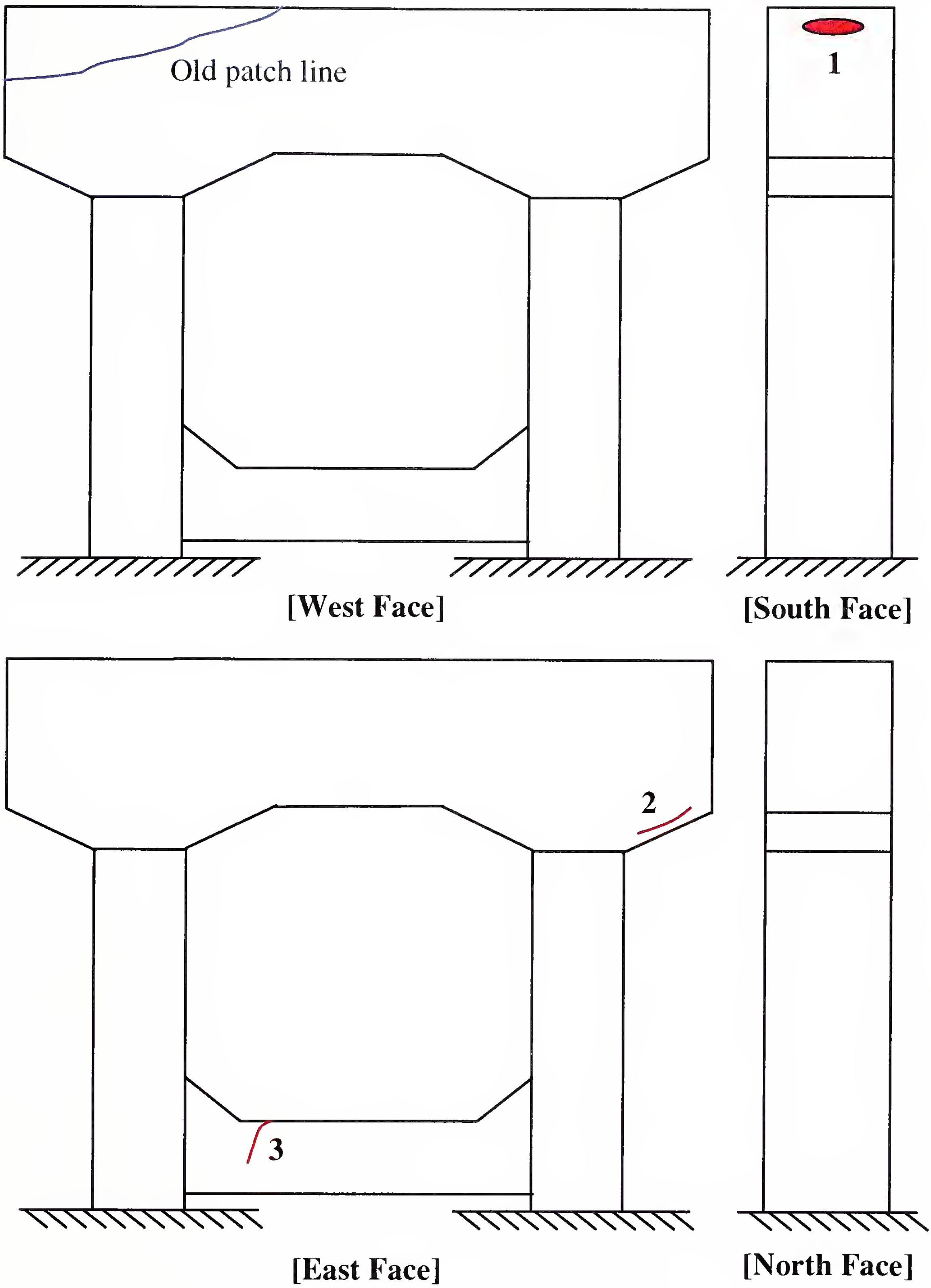
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage
	Cap	West	A crack (1)	
				Test Performed: None

Figure 50A. Condition of Bent No. 20 (West Bound).



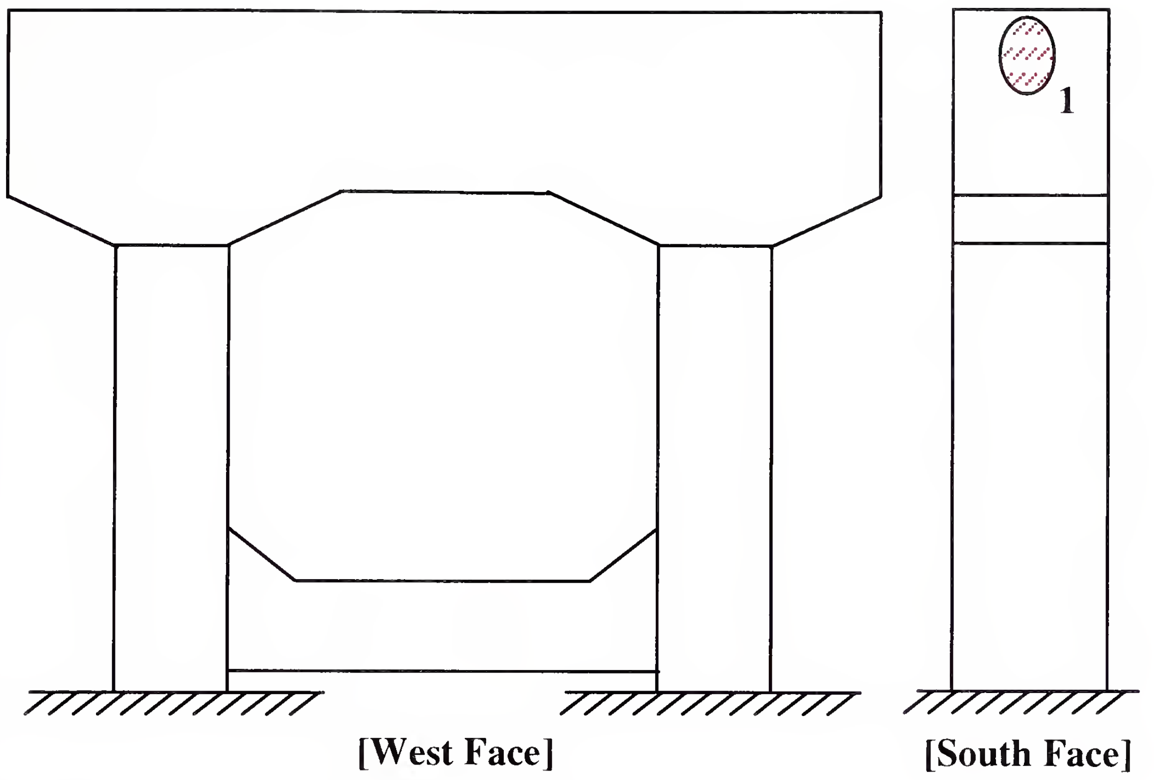
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Wet below beams 4-5 and moist below 3-4 Test Performed: None
	Cap	South	Two cracks (1)	
	Cap	East	Two cracks (2)	
	S. Col.	East	Spall and a crack along edge (3)	

Figure 51A. Condition of Bent No. 21 (West Bound).



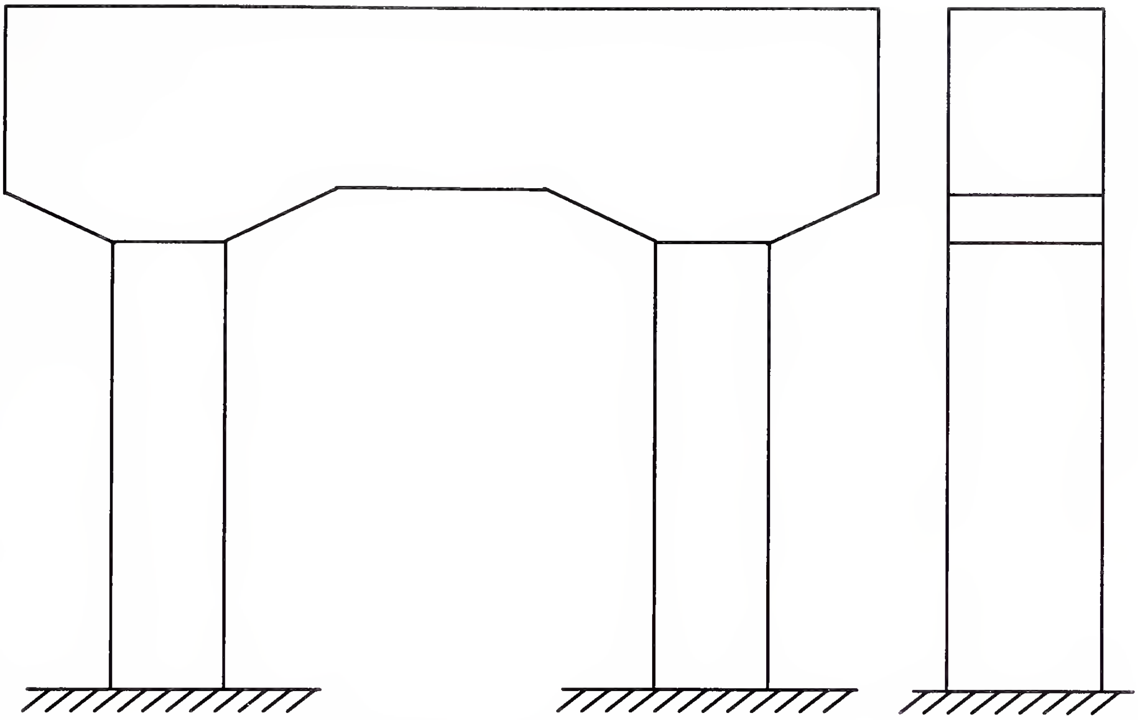
	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage Test Performed: None
Damage	Cap	South	Small spall (1)	
	Cap	East	A crack (2)	
	Beam	East	A crack (3)	

Figure 52A. Condition of Bent No. 22 (West Bound).

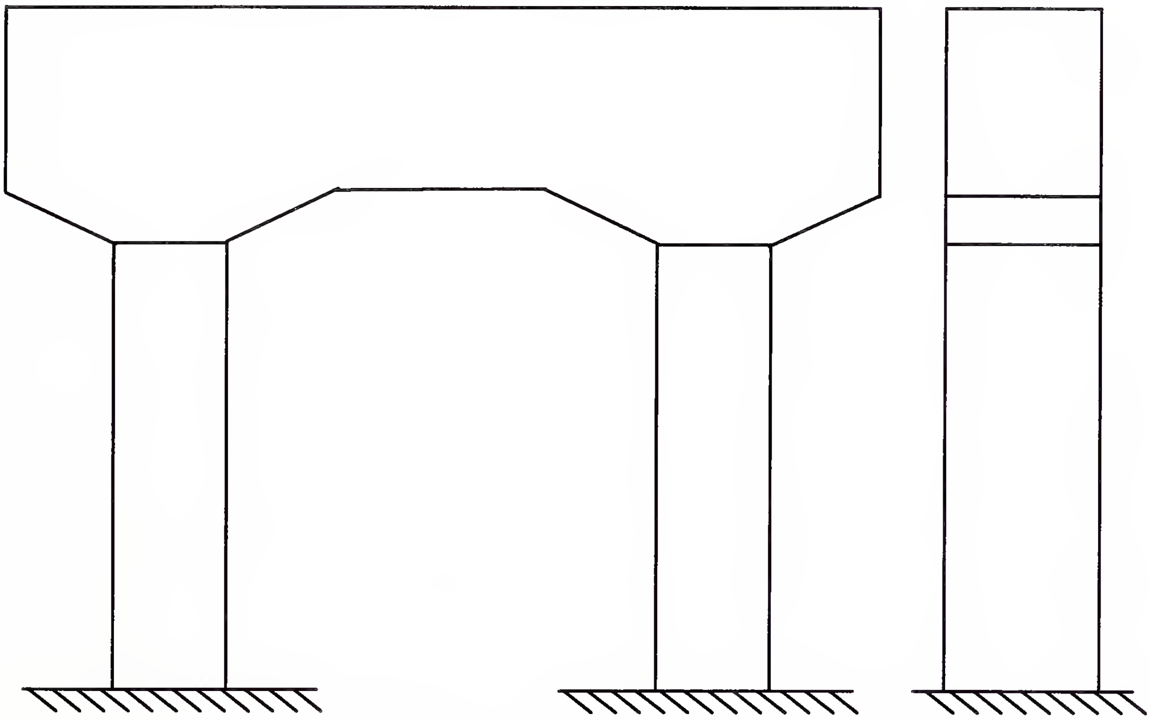


Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage below beams 3-5 and dry stains Test Performed: None
	Cap	South	Multiple cracks (1)	

Figure 53A. Condition of Bent No. 23 (West Bound).



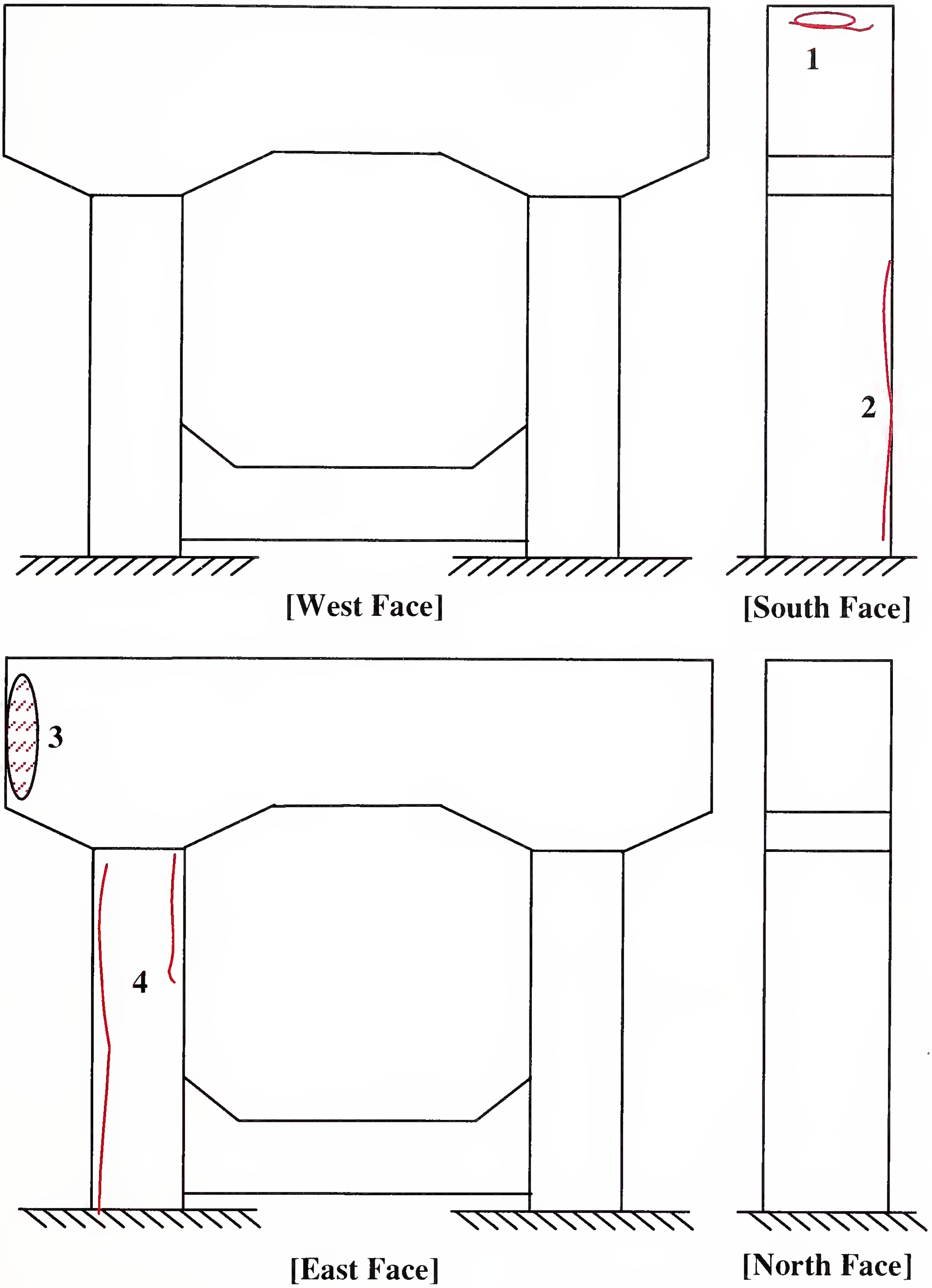
[West Face] [South Face]



[East Face] [North Face]

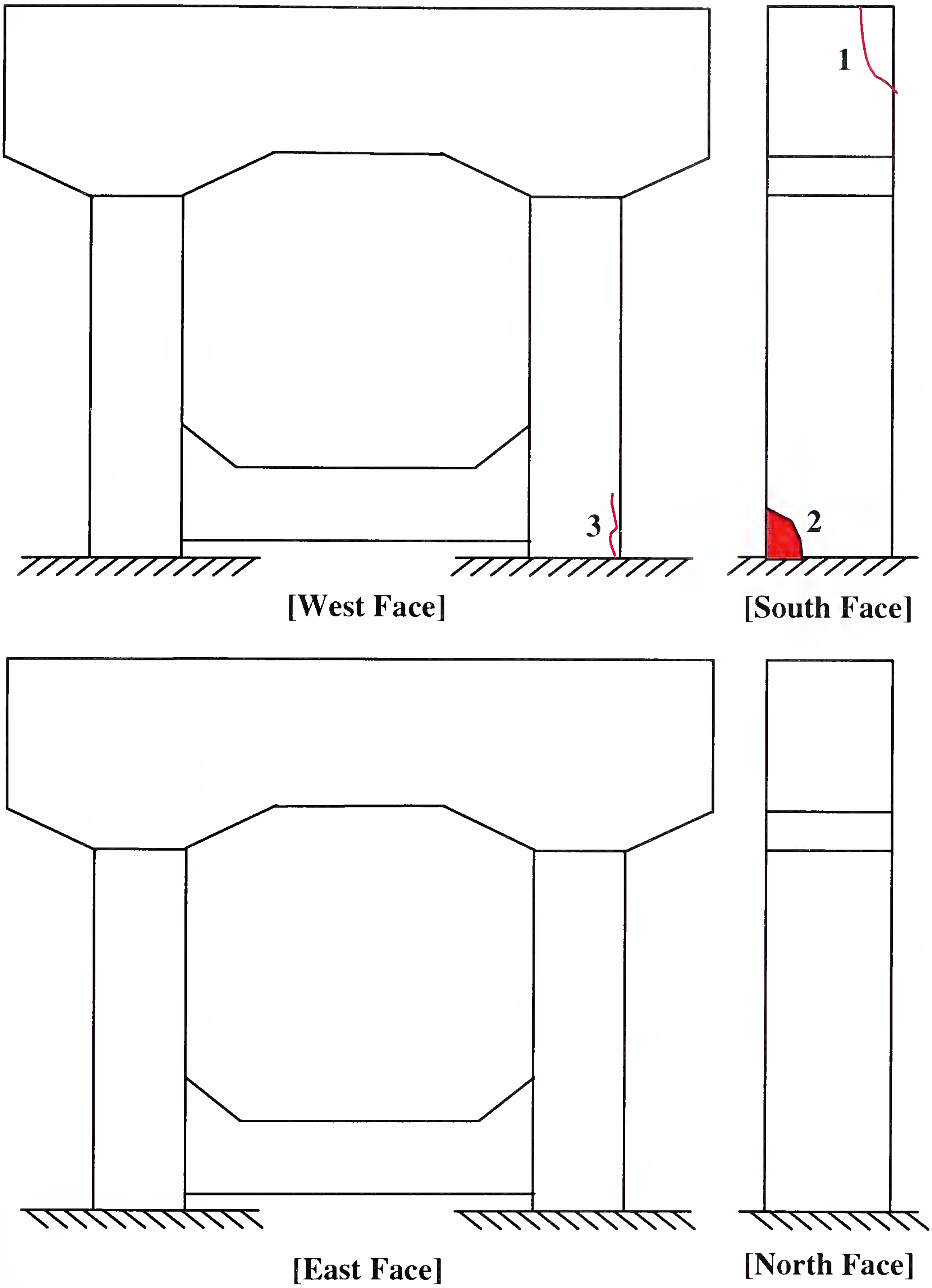
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but dry stains Test Performed: None
			No Damage Observed	

Figure 54A. Condition of Bent No. 24 (West Bound).



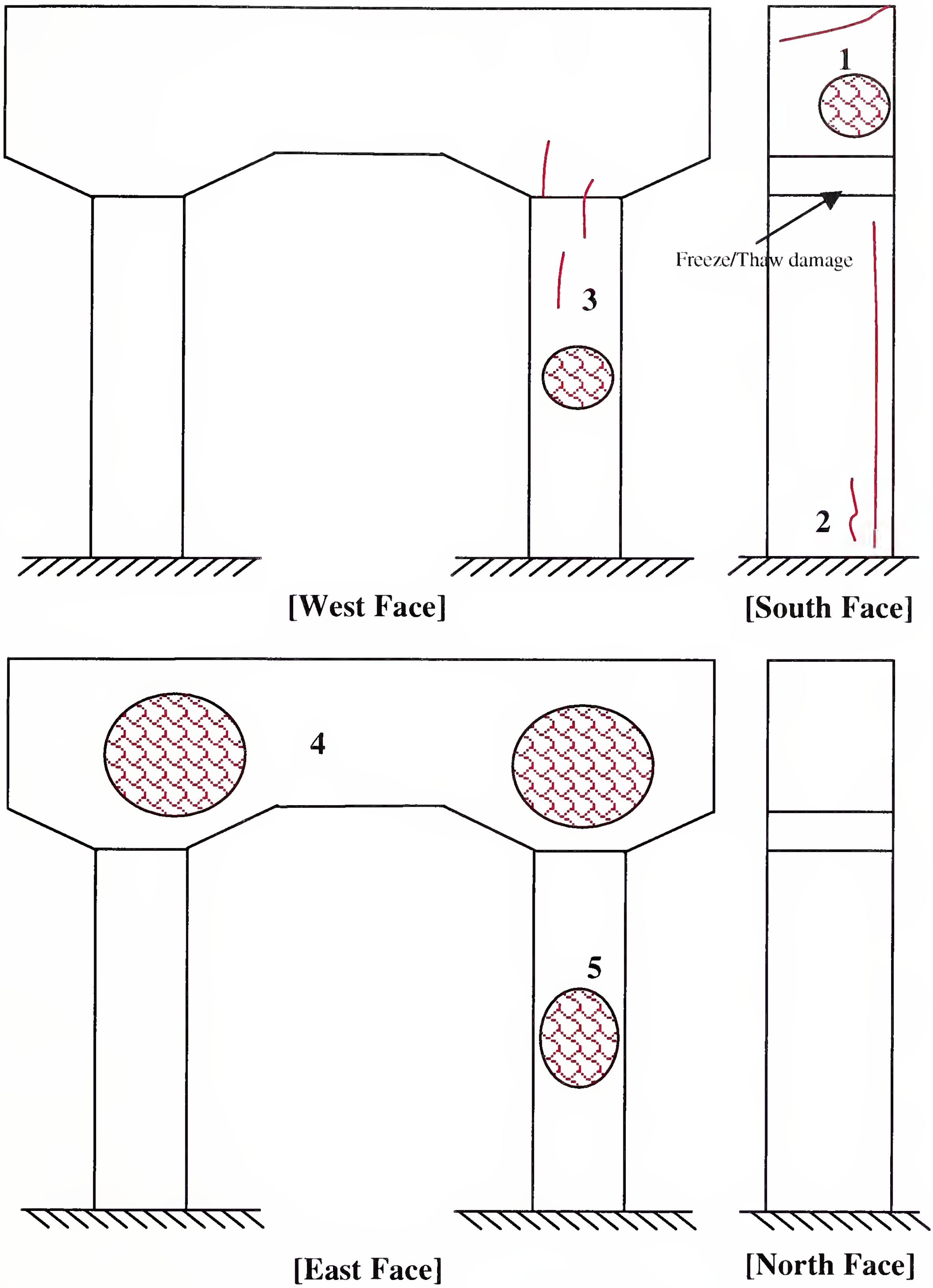
	Location	Face	Description of Damage (No.)	Leakage Condition: Joint moist and south column wet due to a drainage pipe nearby Test Performed: None
Damage	Cap	South	Delamination and a crack (1)	
	S. Col.	South	A crack (2)	
	Cap	East	Multiple cracks (3)	
	S. Col.	East	Two cracks(4)	

Figure 55A. Condition of Bent No. 25 (West Bound).



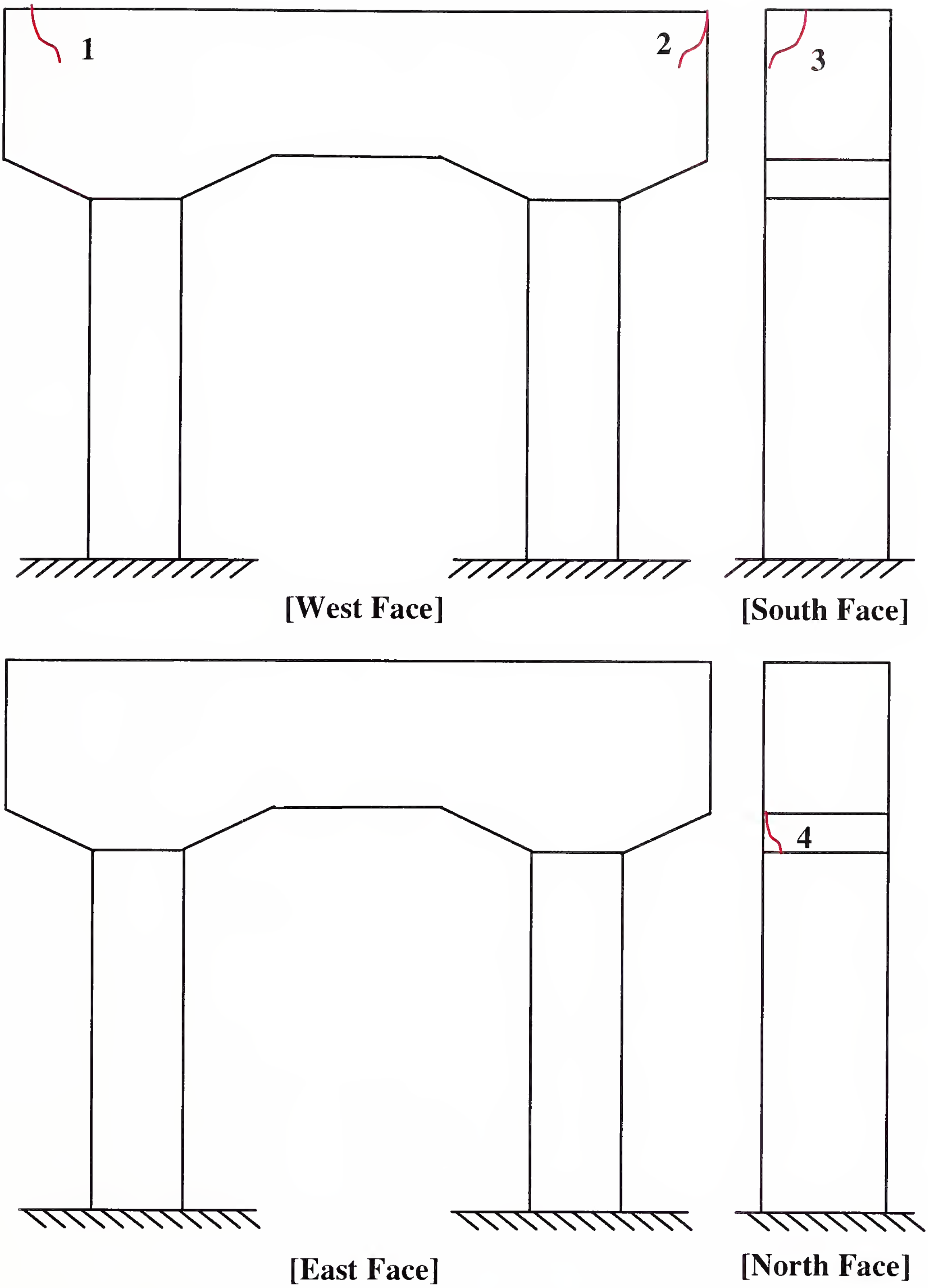
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No Leakage Test Performed: None
	Cap	South	A crack (1)	
	S. Col.	West	Spall and freeze-thaw damage (2)	
	S. Col.	West	A crack (3)	

Figure 56A. Condition of Bent No. 26 (West Bound).



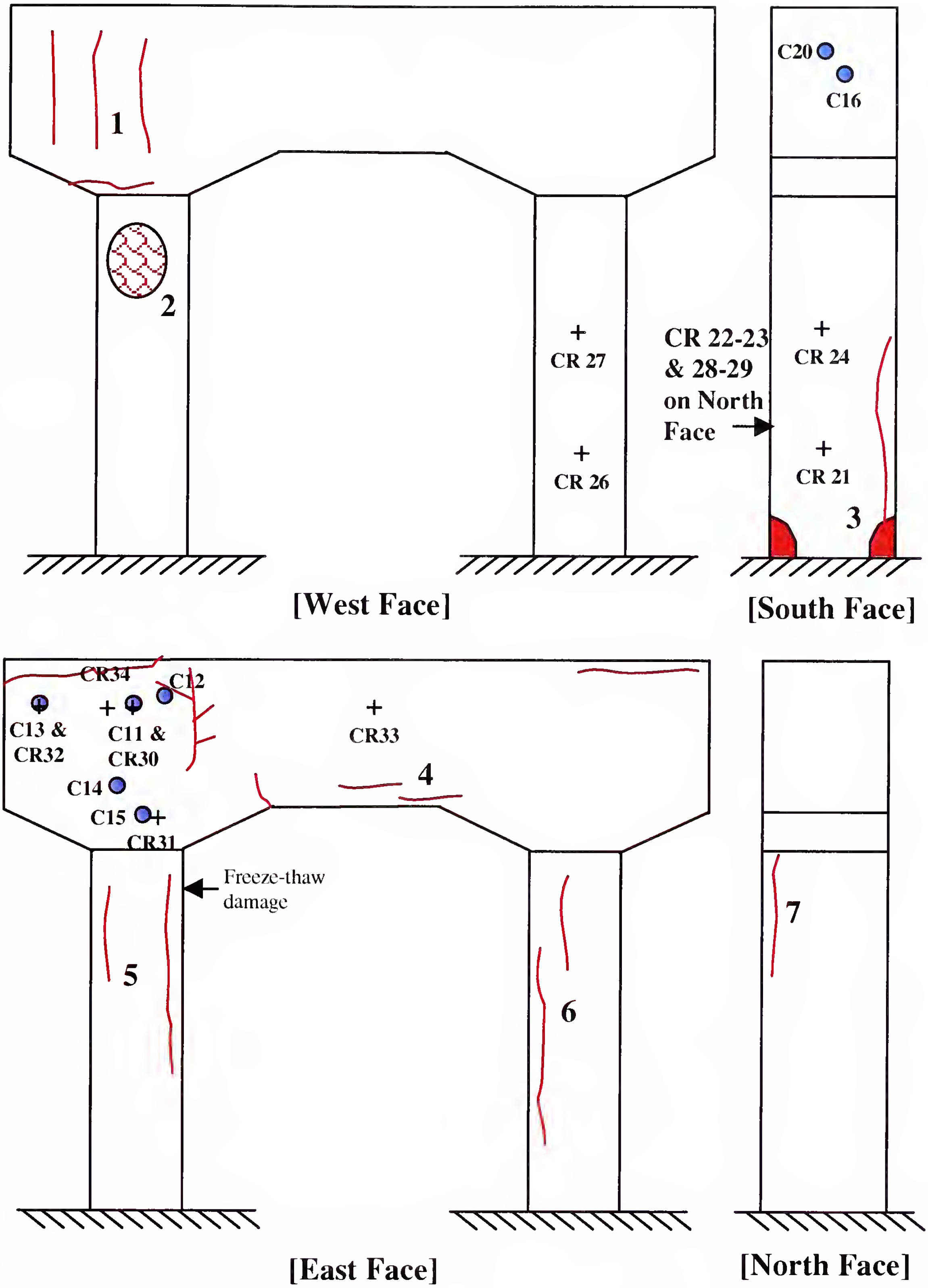
	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage on south column Test Performed: None
Damage	Cap	South	A crack and pattern cracking (1)	
	S. Col.	South	Two cracks (2)	
	S. Col.	West	3 cracks and pattern cracking (3)	
	Cap	East	Two pattern cracking areas (4)	
	N. Col.	East	Pattern cracking (5)	

Figure 57A. Condition of Bent No. 27 (West Bound).



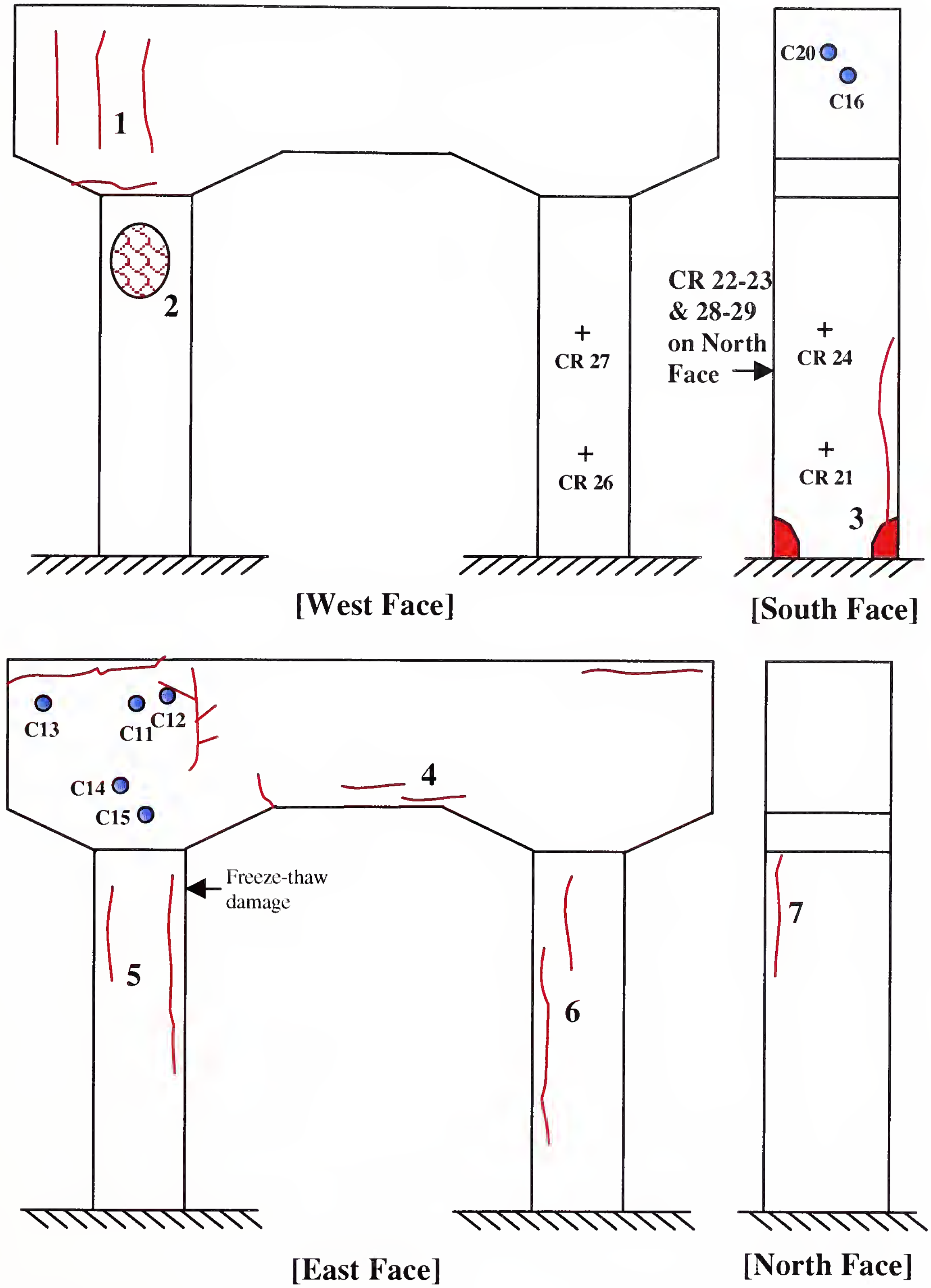
Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but dry stains Test Performed: None
	Cap	West	A crack (1)	
	Cap	West	A crack (2)	
	Cap	South	A crack (3)	
	Cap	North	A crack (1)	

Figure 58A. Condition of Bent No. 28 (West Bound).



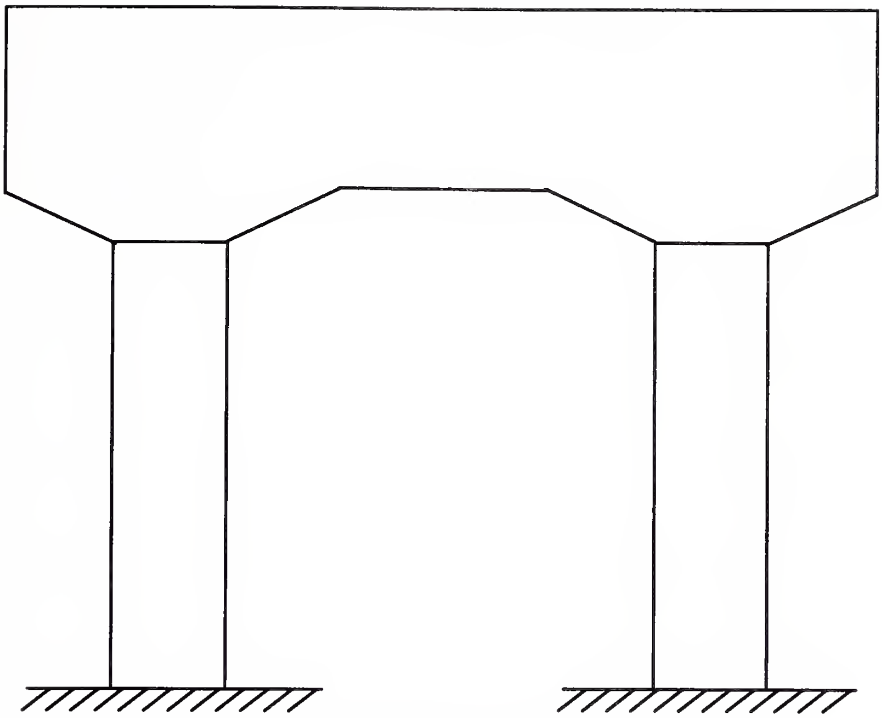
	Location	Face	Description of Damage (No.)	
Damage	Cap	West	Four cracks (1)	Leakage Condition: Active leakage under beams 2-5
	N. Col.	West	Pattern cracking (2)	
	S. Col.	South	Two spalls and a crack (3)	Test Performed:
	Cap	East	Six cracks (4)	- CR 21-24 & 26-34 - Cores 11-16 & 20
	S. Col.	East	Two cracks (5)	- Carbonation Test at 3

Figure 59A.1. Condition of Bent No. 29 (West Bound) - To Be Continued.

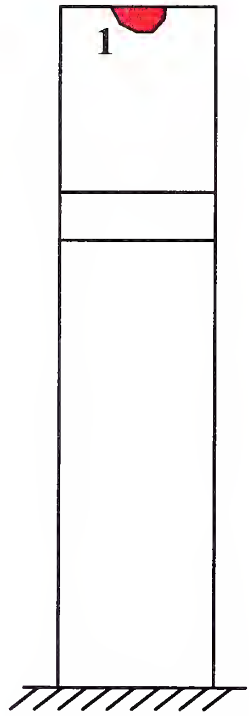


Damage	Location	Face	Description of Damage (No.)	Leakage Condition: Active leakage under beams 1-5 (3-5 worst)
	N. Col.	East	Two cracks (6)	
	N. Col.	North	A crack (7)	
				Test Performed: - CR 21-24 & 26-29 - Cores 11-16 & 20 - Carbonation Test at 3

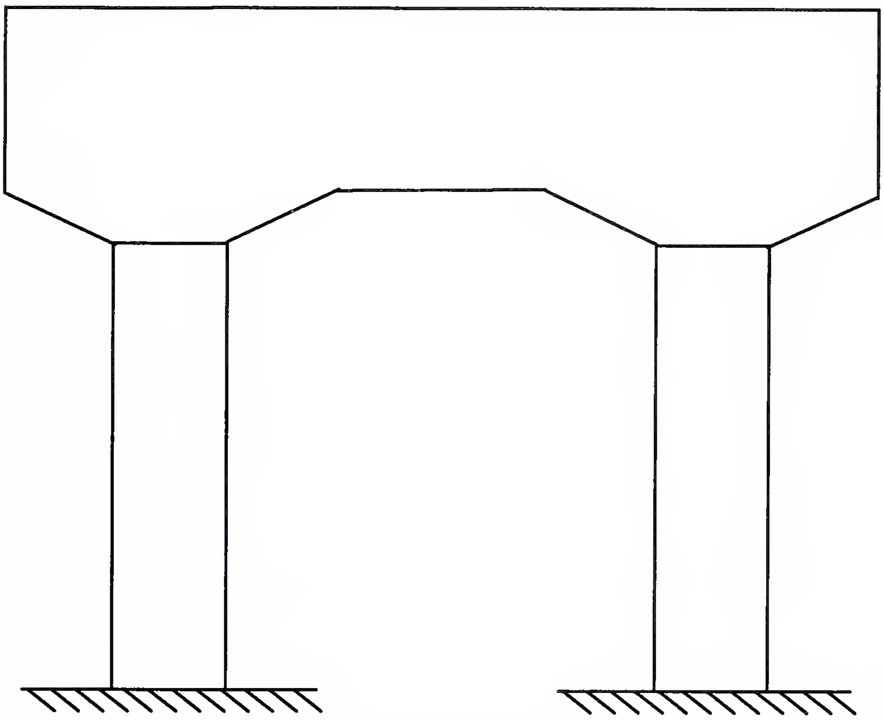
Figure 59A.2. Condition of Bent No. 29 (West Bound) - Continued.



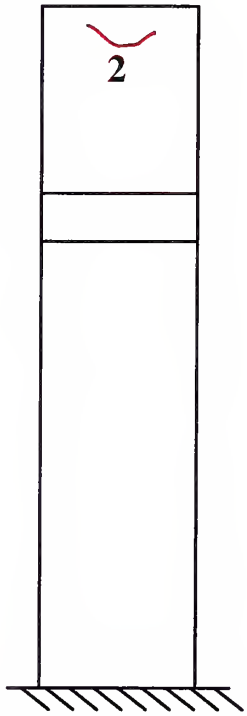
[West Face]



[South Face]



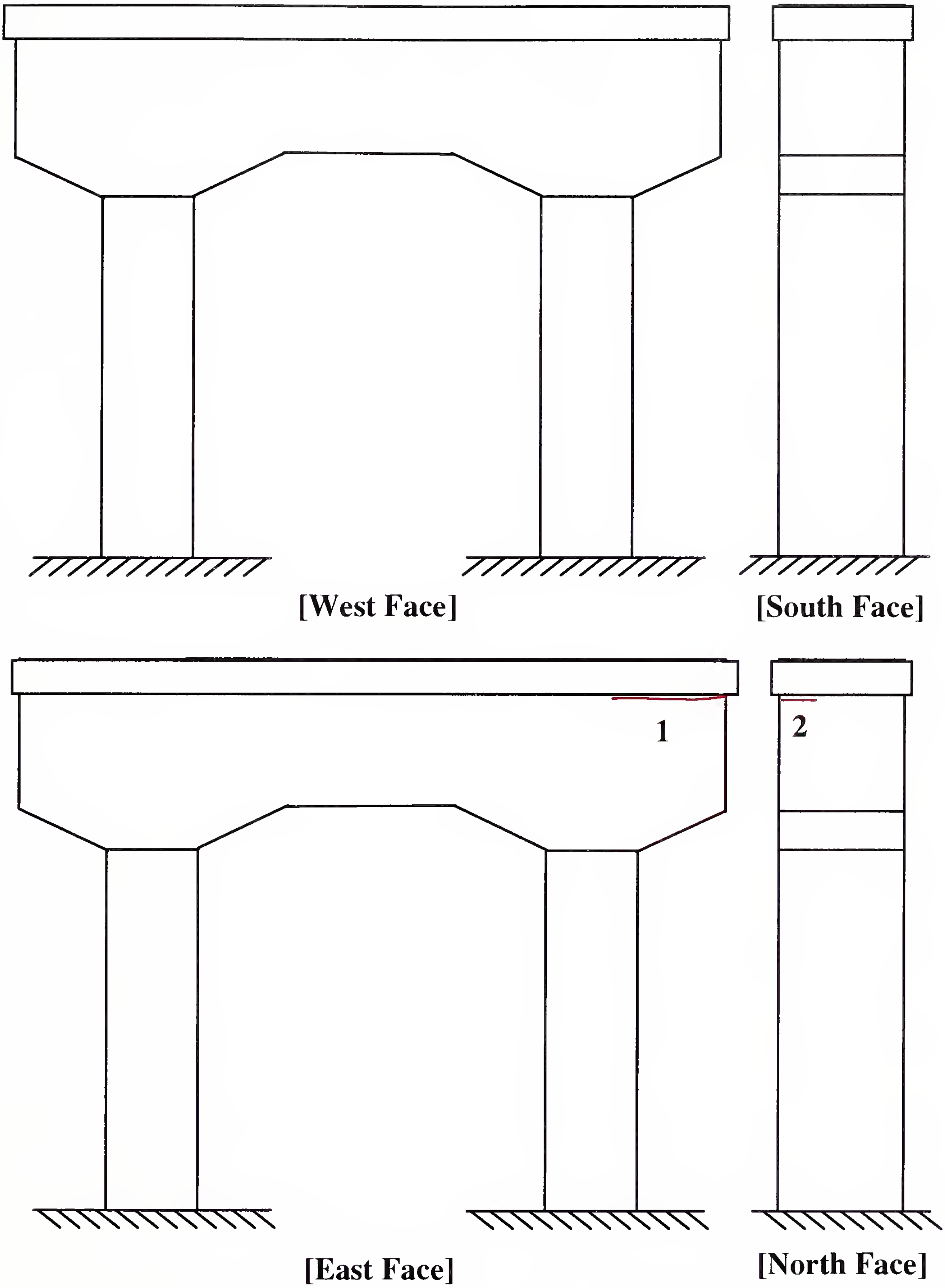
[East Face]



[North Face]

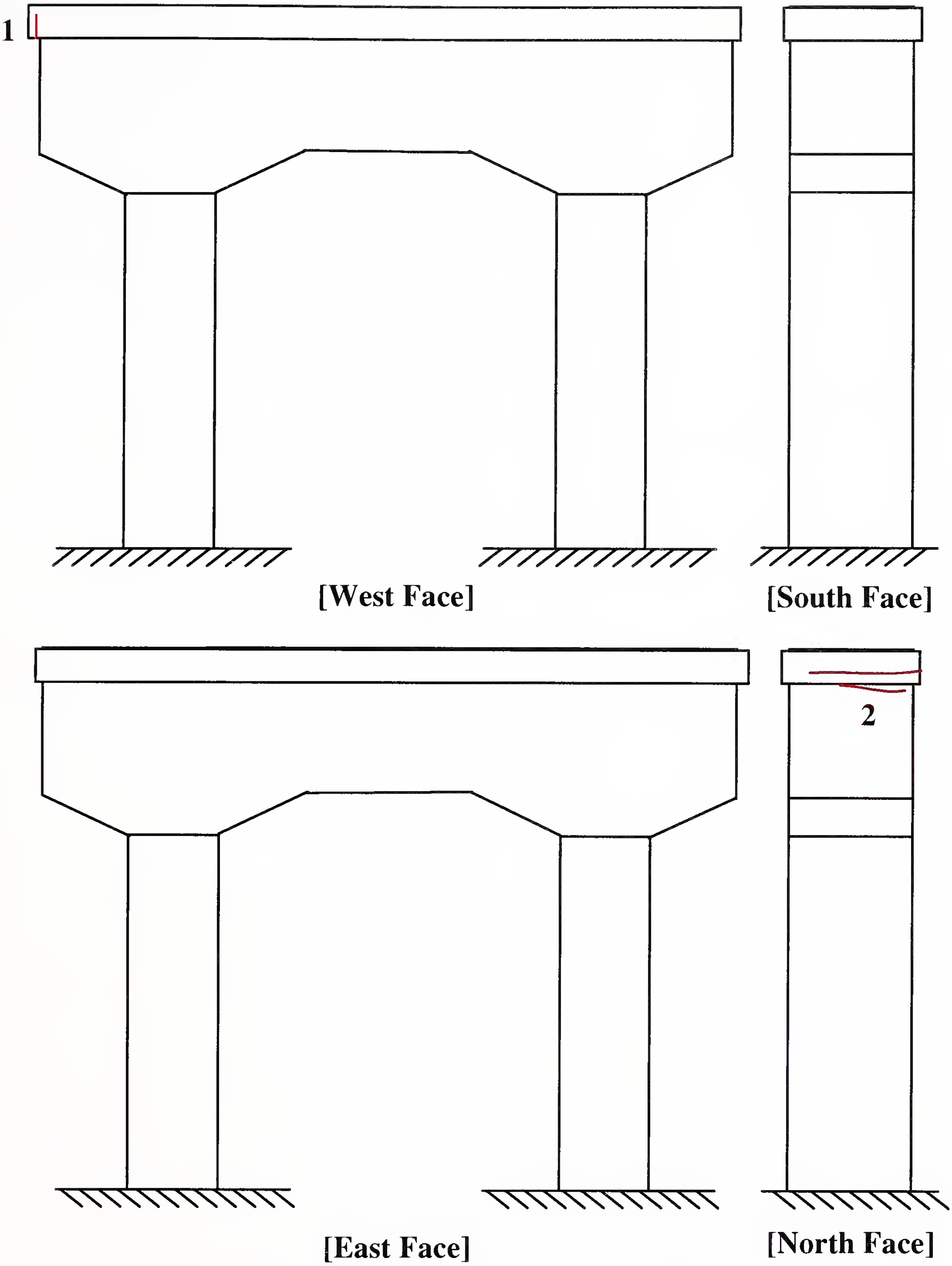
	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but dry stains Test Performed: None
Damage	Cap	South	Small spall (1)	
	Cap	North	A crack (2)	

Figure 60A. Condition of Bent No. 30 (West Bound).



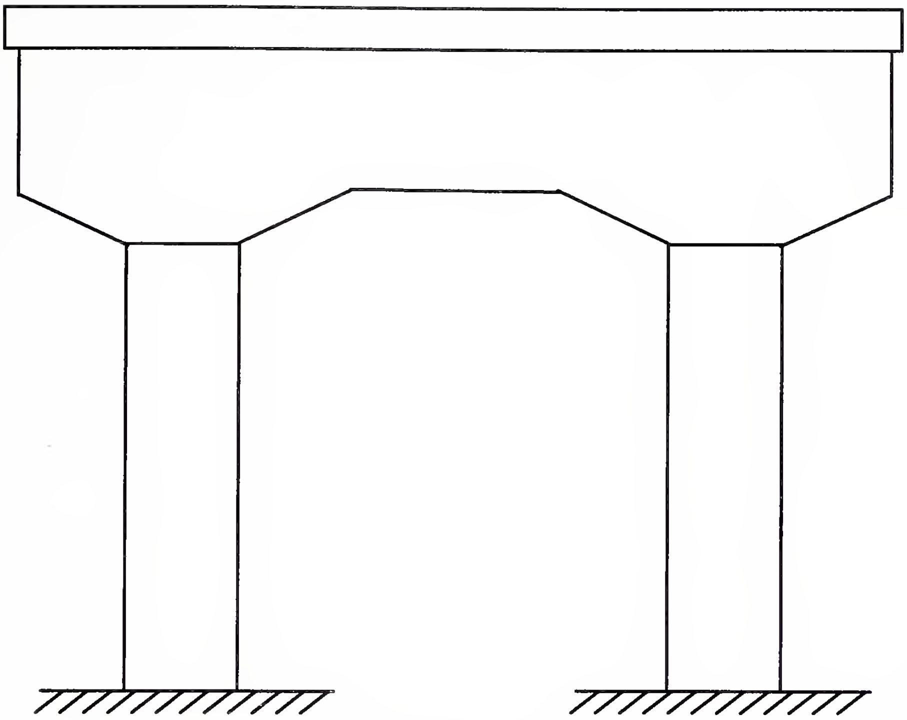
Damage	Location	Face	Description of Damage (No.)	Leakage Condition:
	Cap	East	A crack (1)	Active leakage below beams 1-4
	Cap	North	A crack (2)	
				Test Performed: None

Figure 61A. Condition of Bent No. 31 (West Bound).

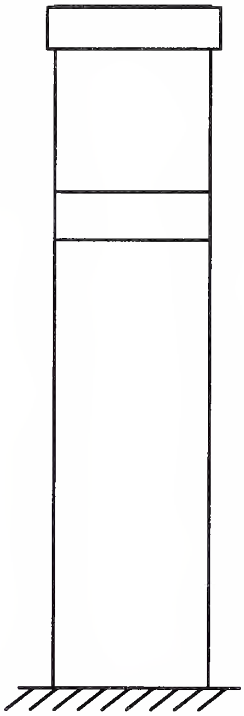


Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but moist below beams 1-2
	Cap	West	A crack on top cap (1)	
	Cap	North	Cracks on top cap and underside(2)	Test Performed: None

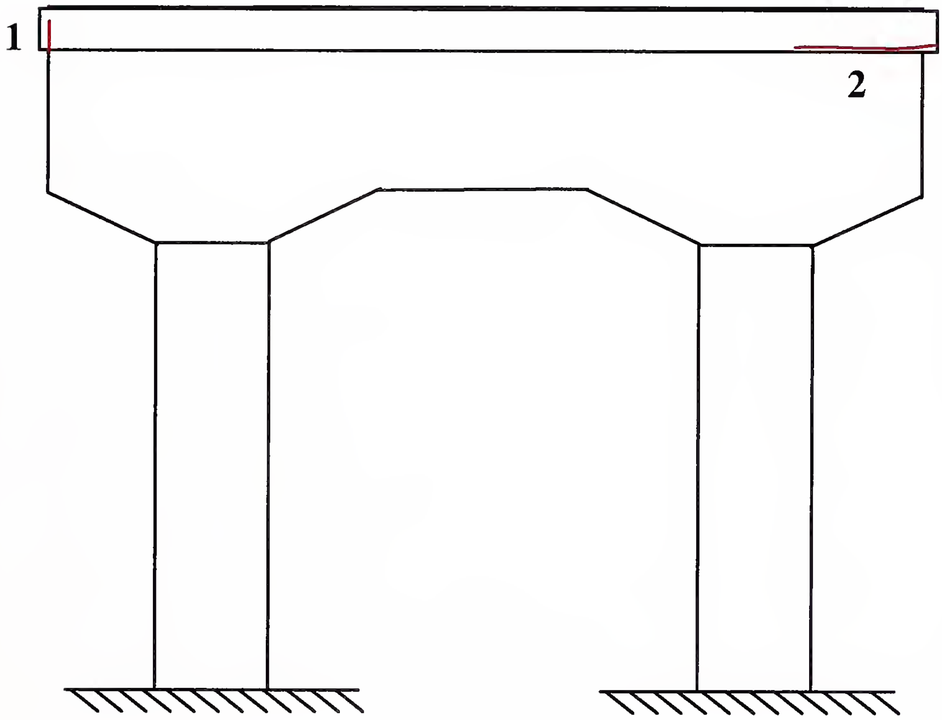
Figure 62A. Condition of Bent No. 32 (West Bound).



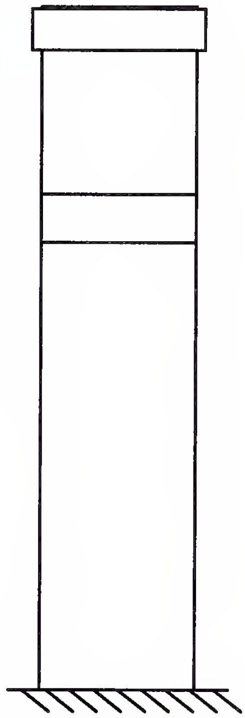
[West Face]



[South Face]



[East Face]



[North Face]

Damage	Location	Face	Description of Damage (No.)	Leakage Condition: No leakage but moist below beams 1-5 Test Performed: None
	Cap	East	A crack on top cap (1)	
	Cap	East	A crack on top cap (2)	

Figure 63A. Condition of Bent No. 33 (West Bound).

APPENDIX B

Condition Survey Data Sheets (Beam Joints)

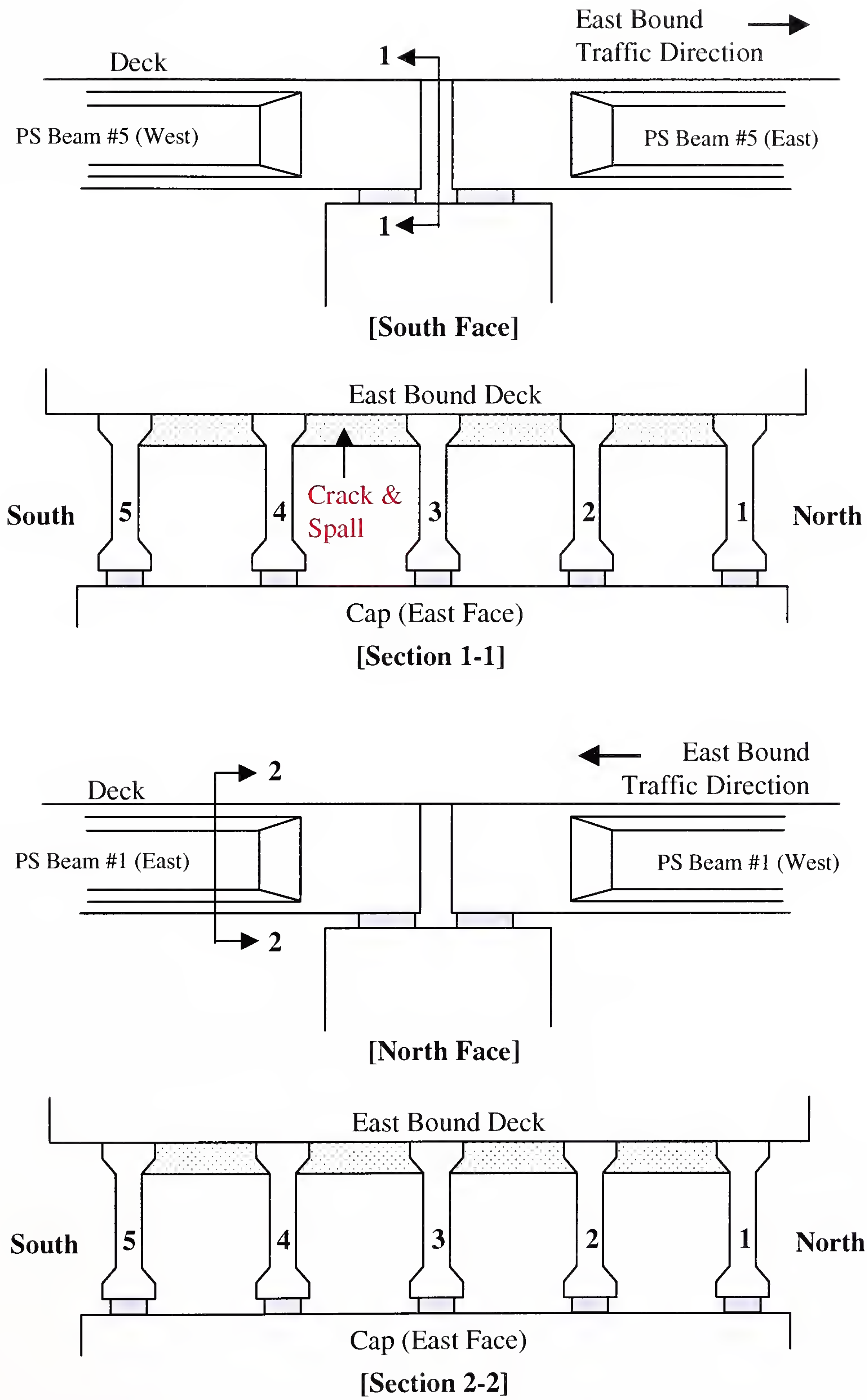


Figure 1B. Condition of Beam Joints over Bent No. 2 (East Bound).

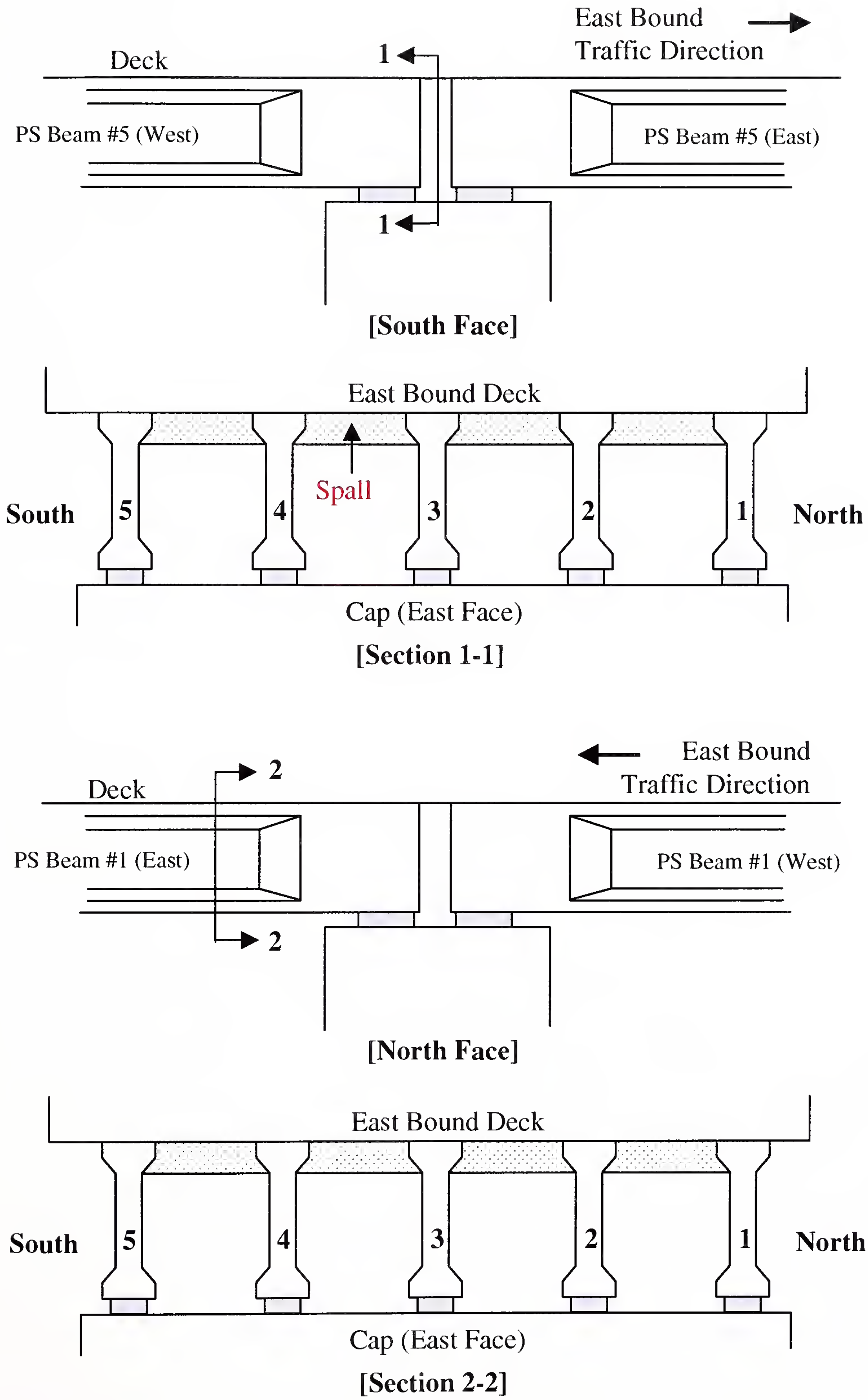


Figure 2B. Condition of Beam Joints over Bent No. 3 (East Bound).

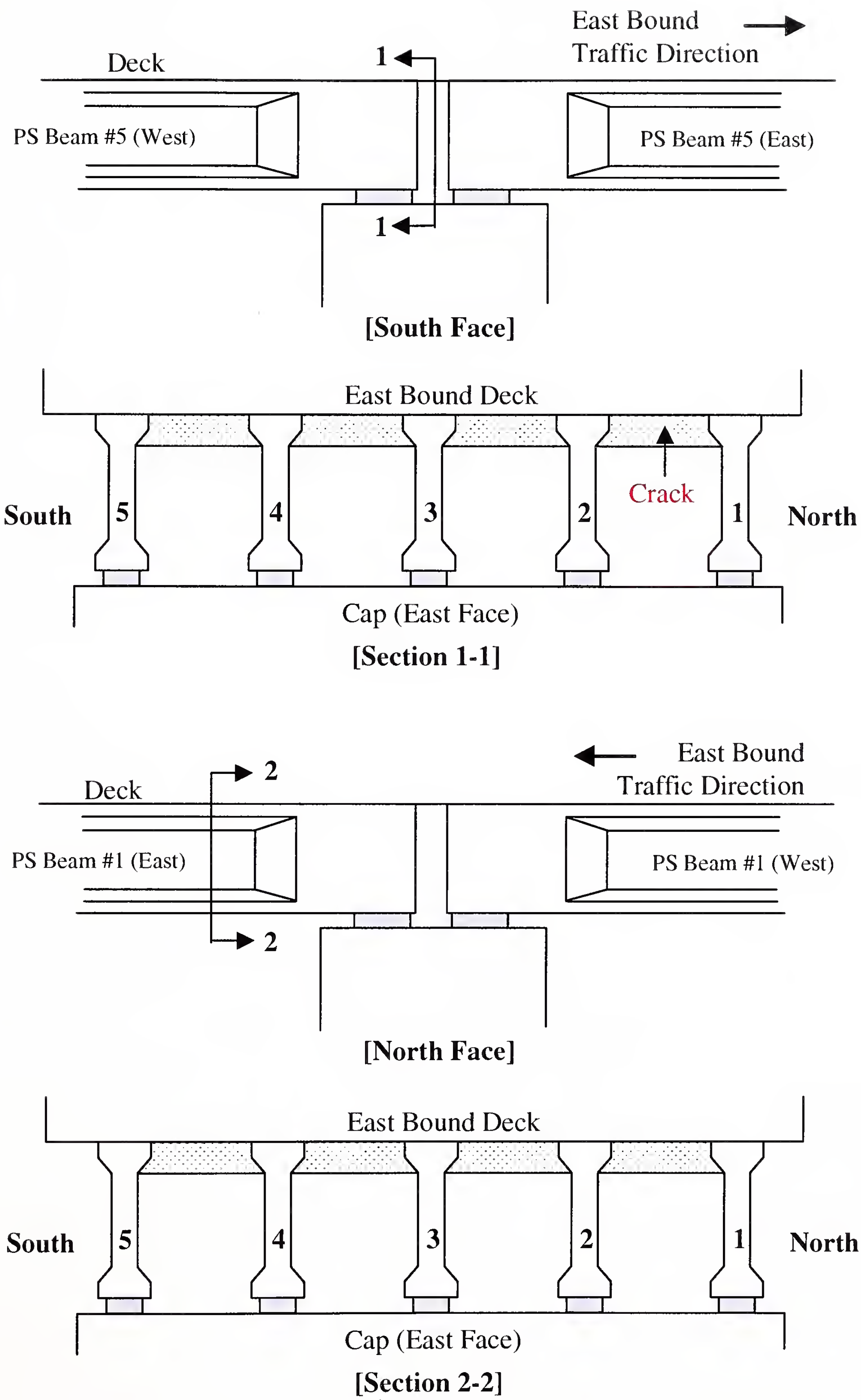


Figure 3B. Condition of Beam Joints over Bent No.4 (East Bound).

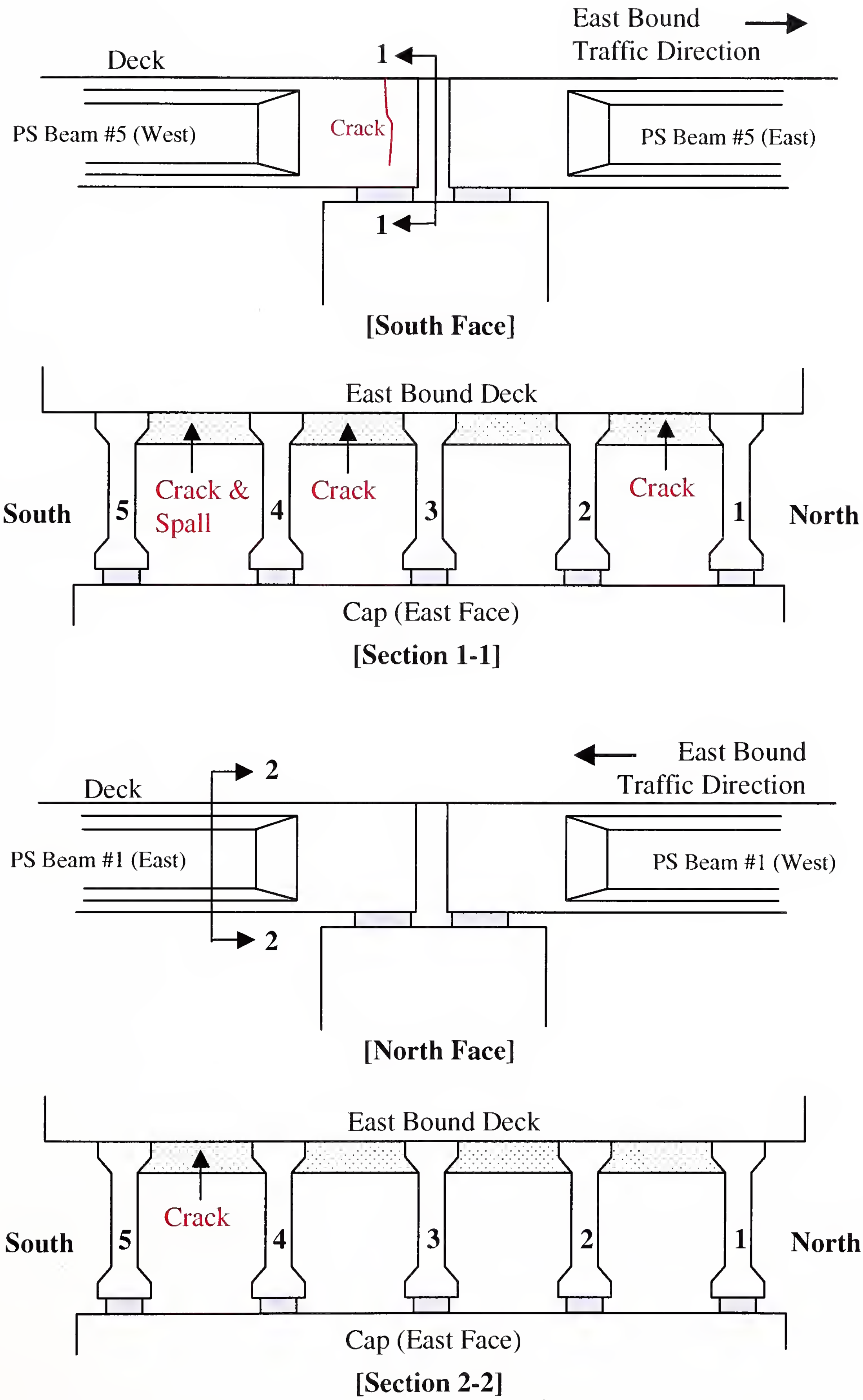


Figure 4B. Condition of Beam Joints over Bent No. 5 (East Bound).

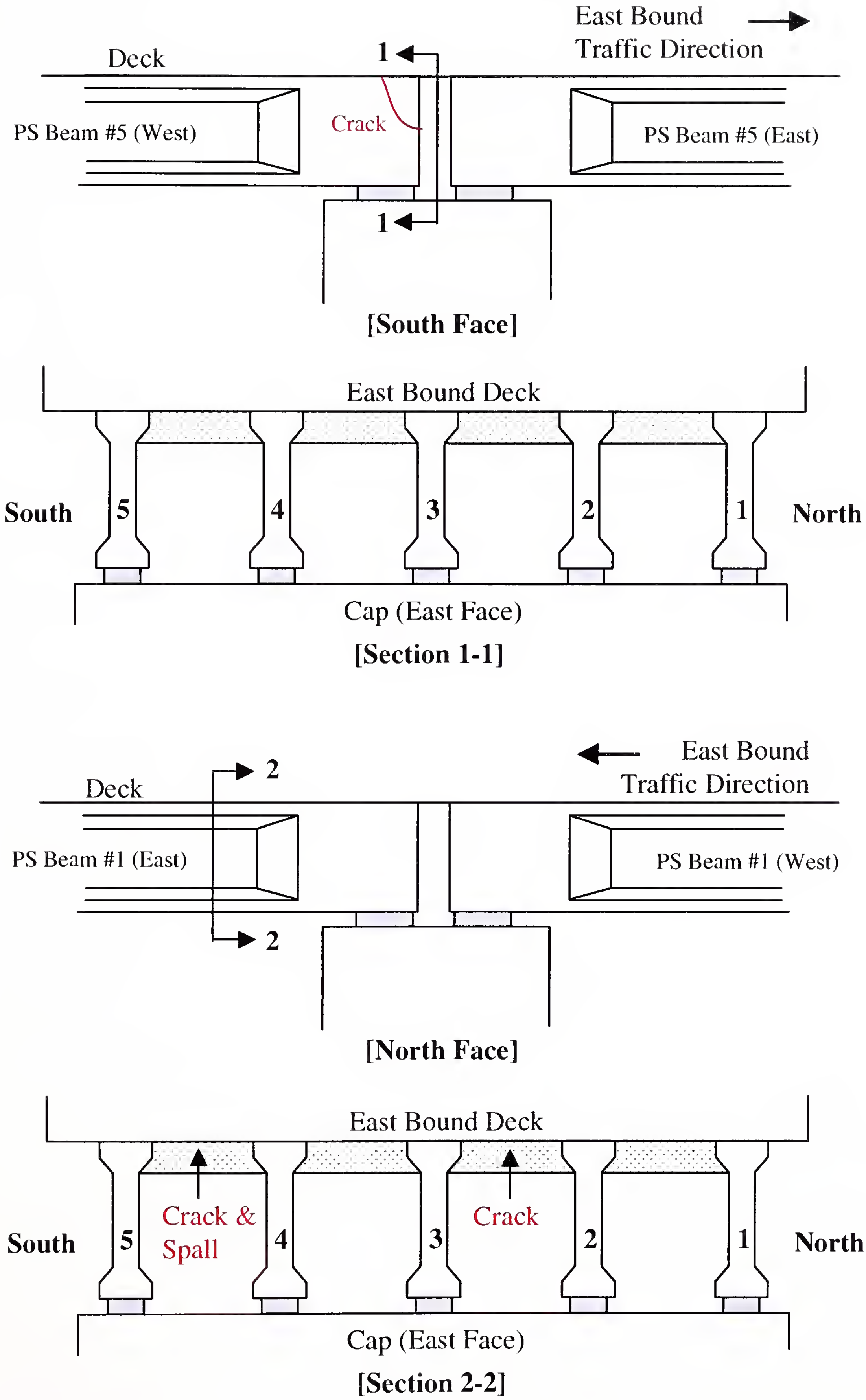


Figure 5B. Condition of Beam Joints over Bent No. 6 (East Bound).

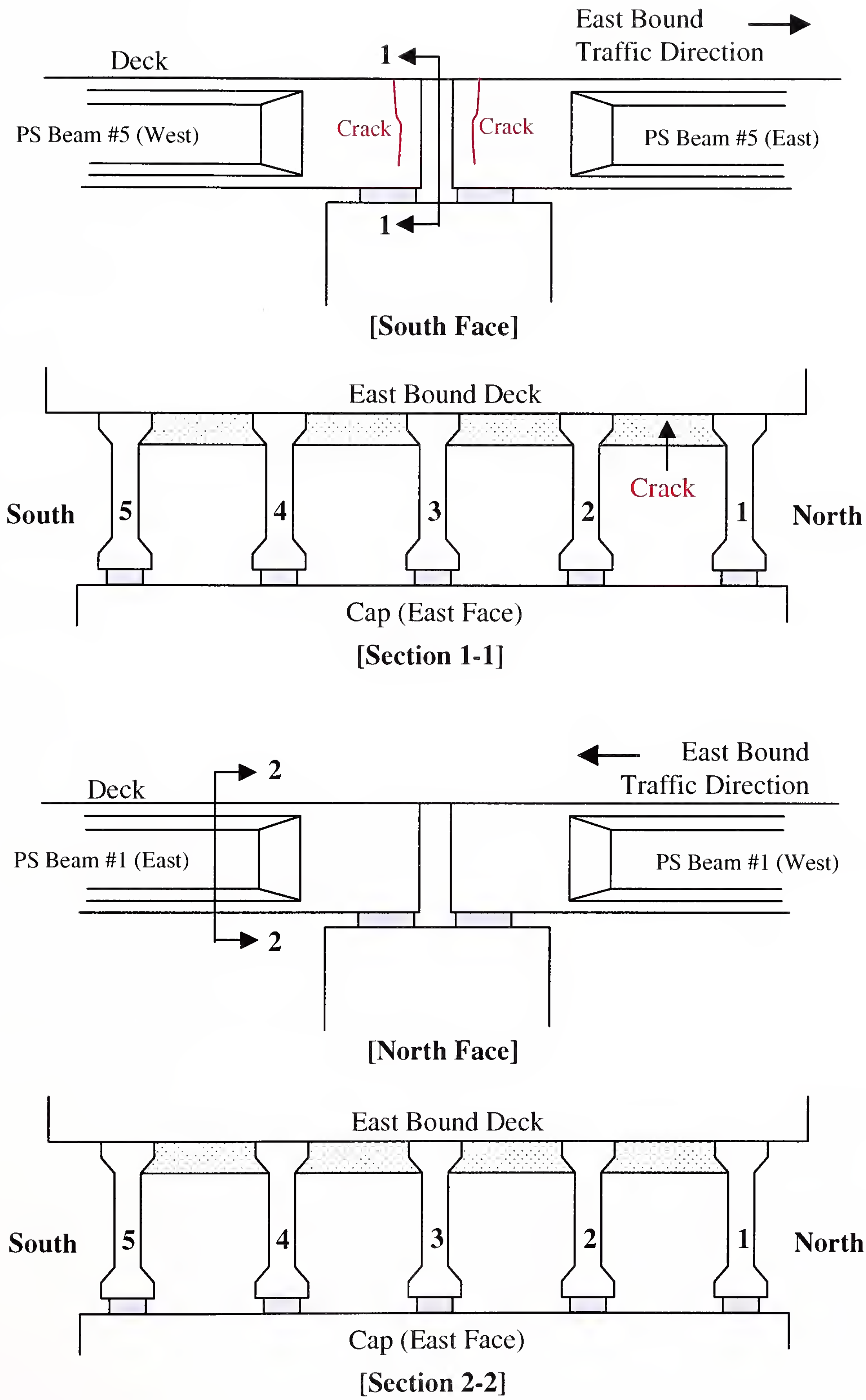


Figure 6B. Condition of Beam Joints over Bent No. 7 (East Bound).

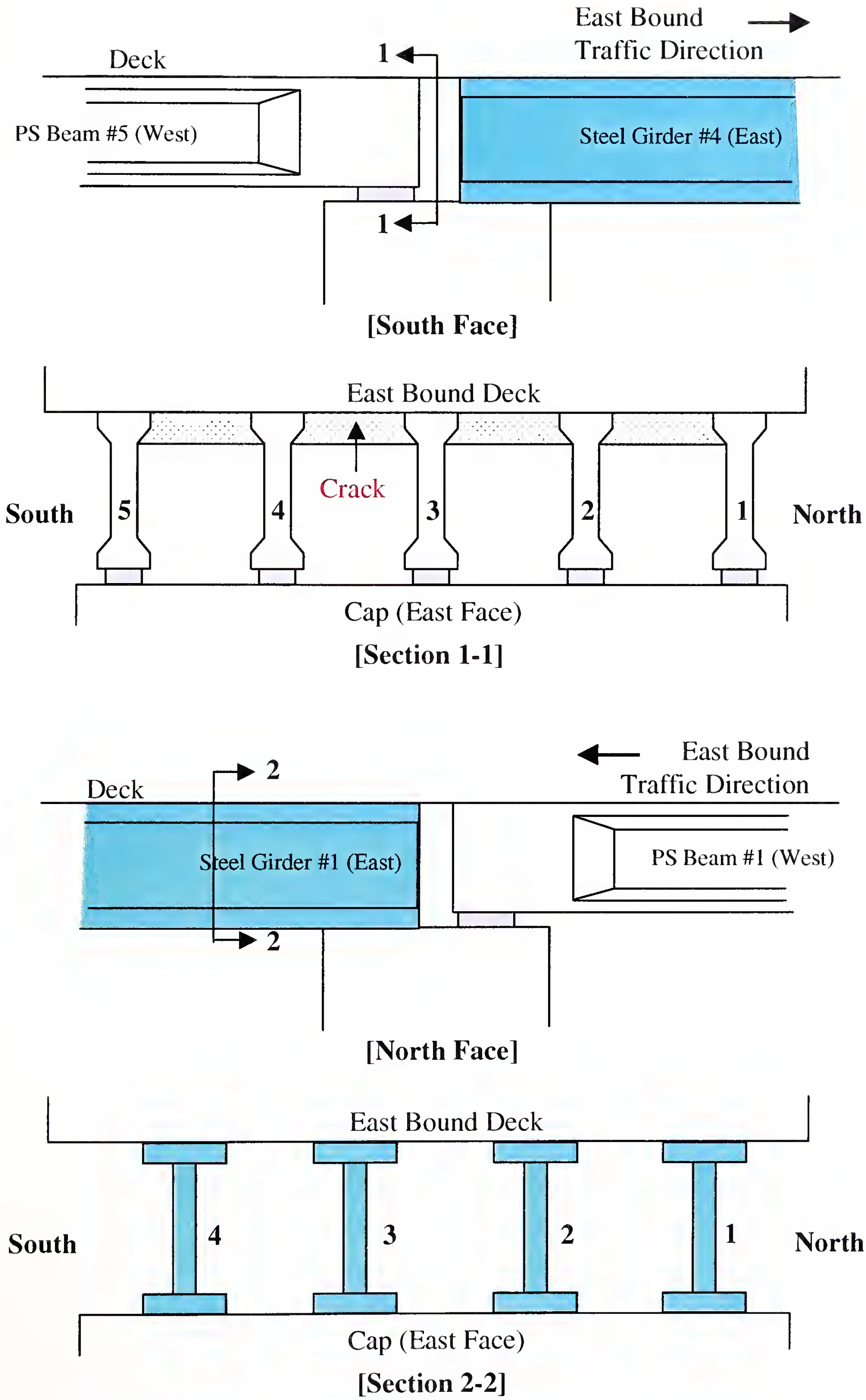


Figure 7B. Condition of Beam Joints over Bent No. 8 (East Bound).

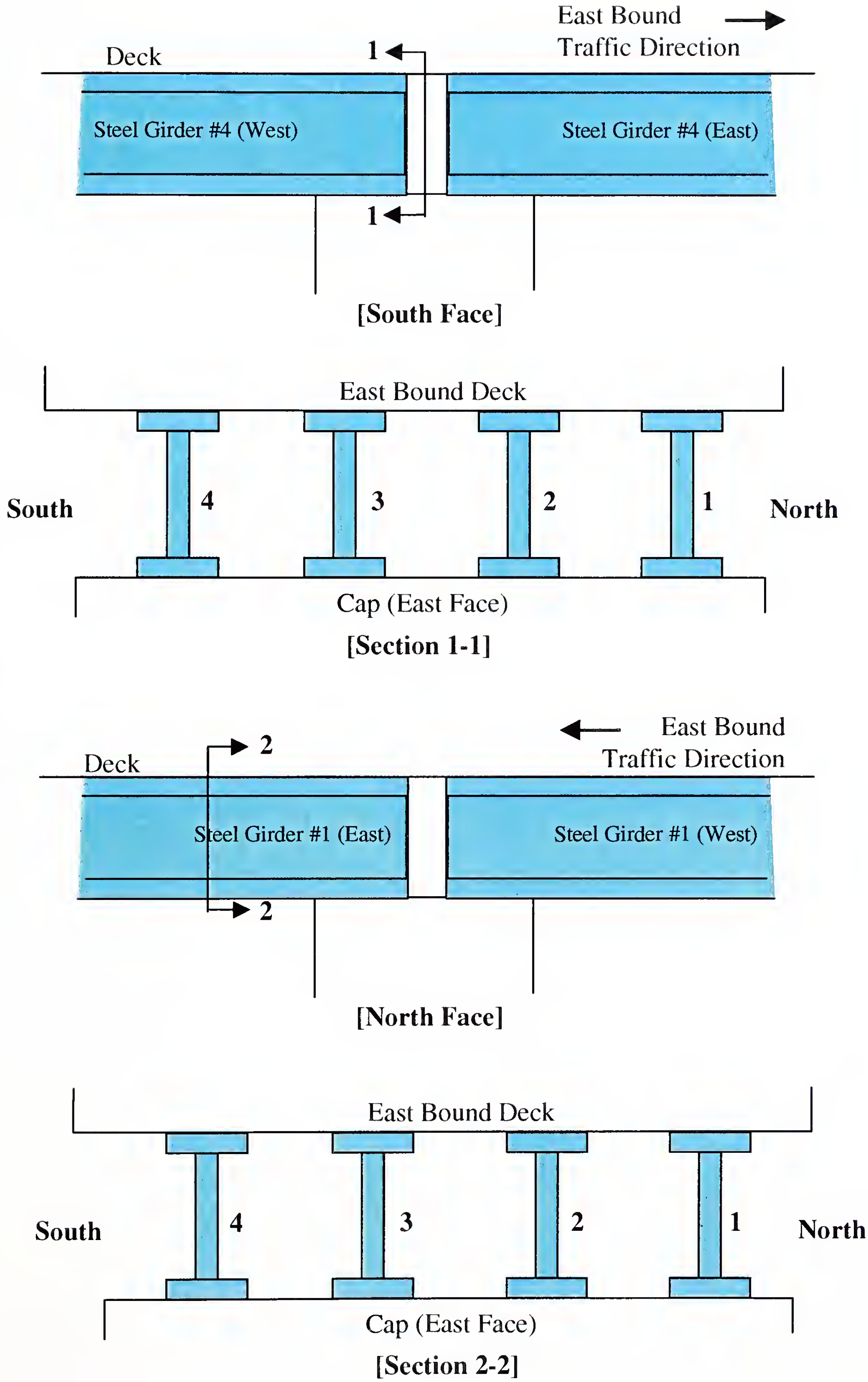


Figure 8B. Condition of Girder Joints over Bent No. 9 (East Bound).

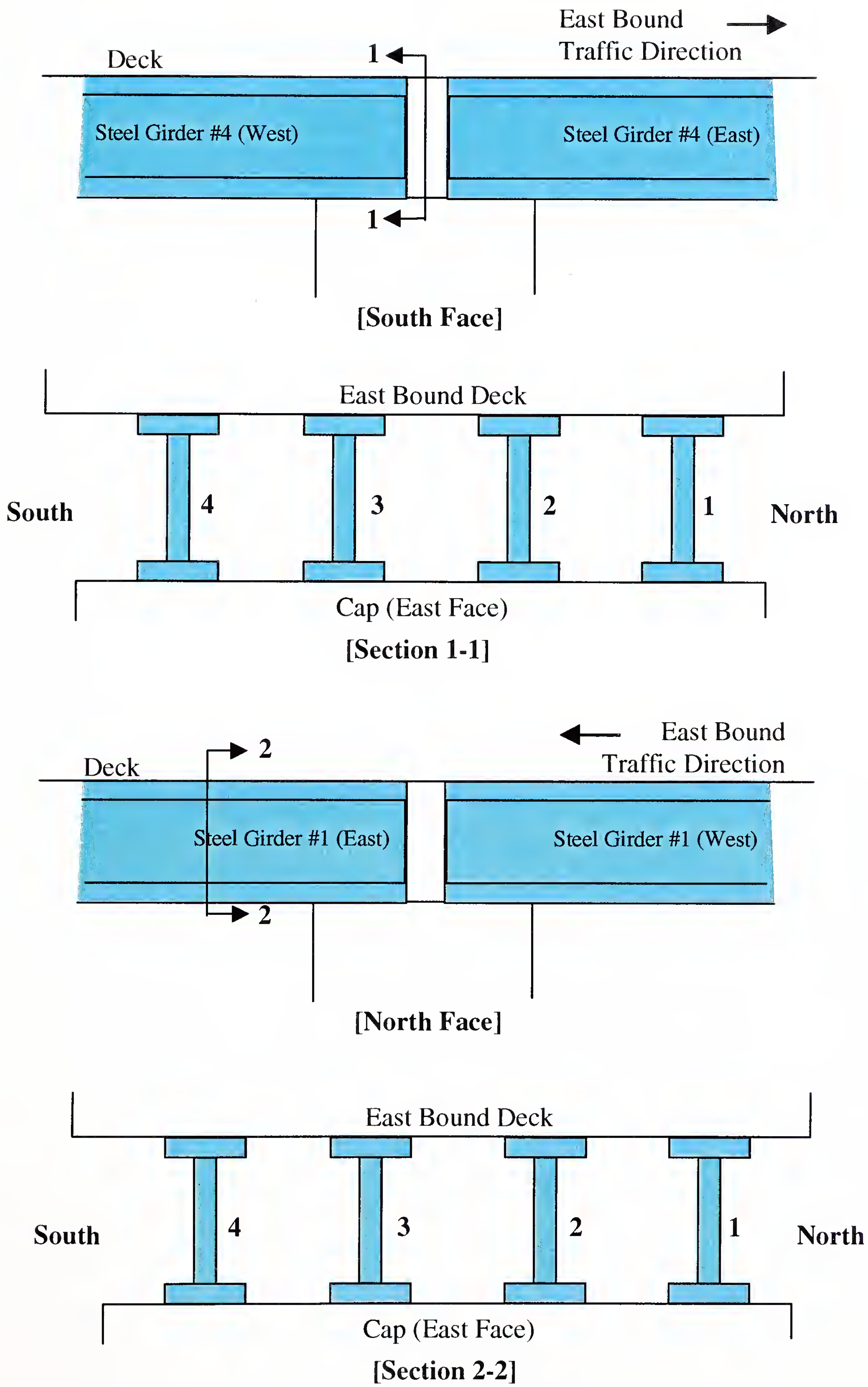


Figure 9B. Condition of Girder Joints over Bent No. 10 (East Bound).

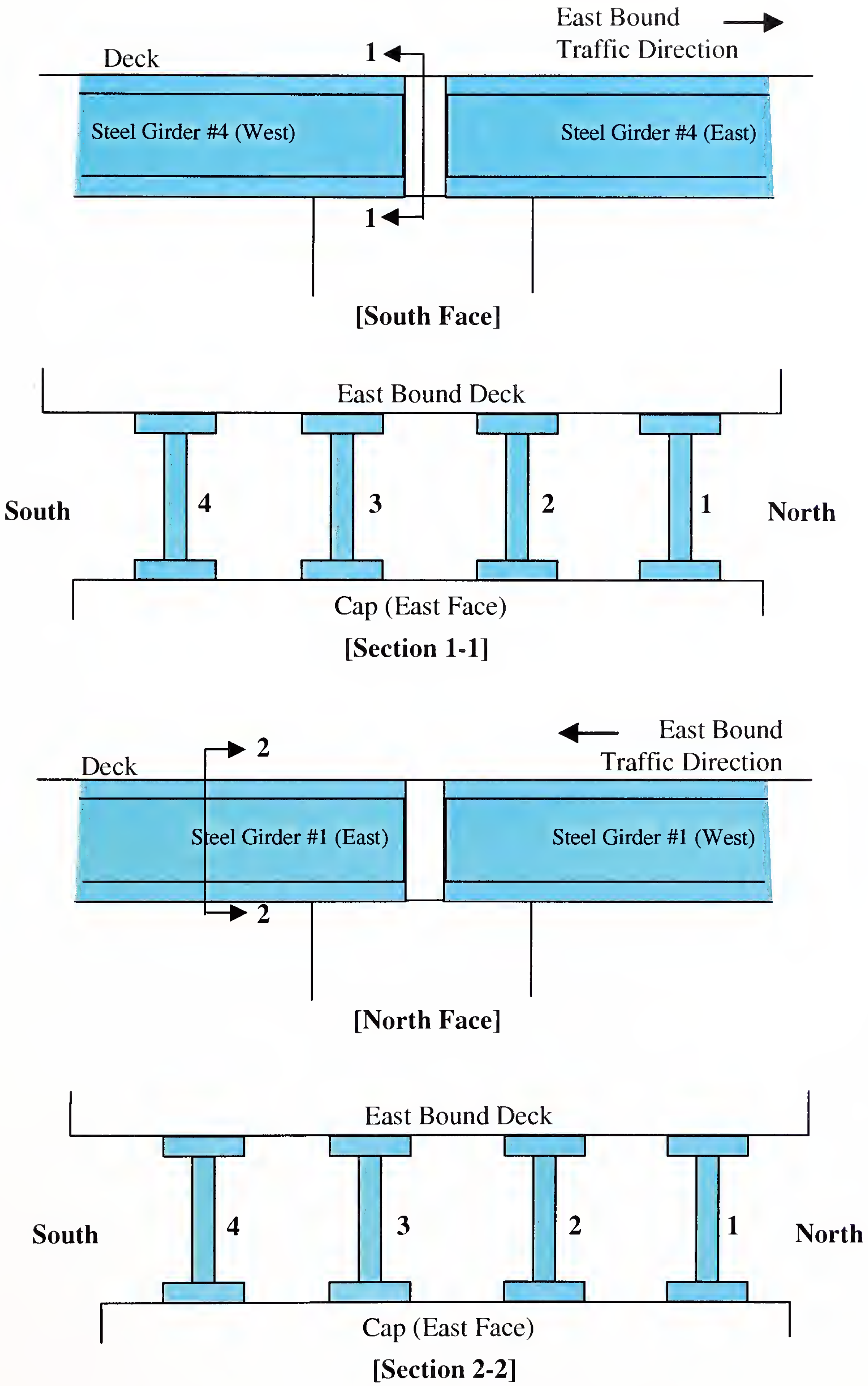


Figure 10B. Condition of Girder Joints over Bent No. 11 (East Bound).

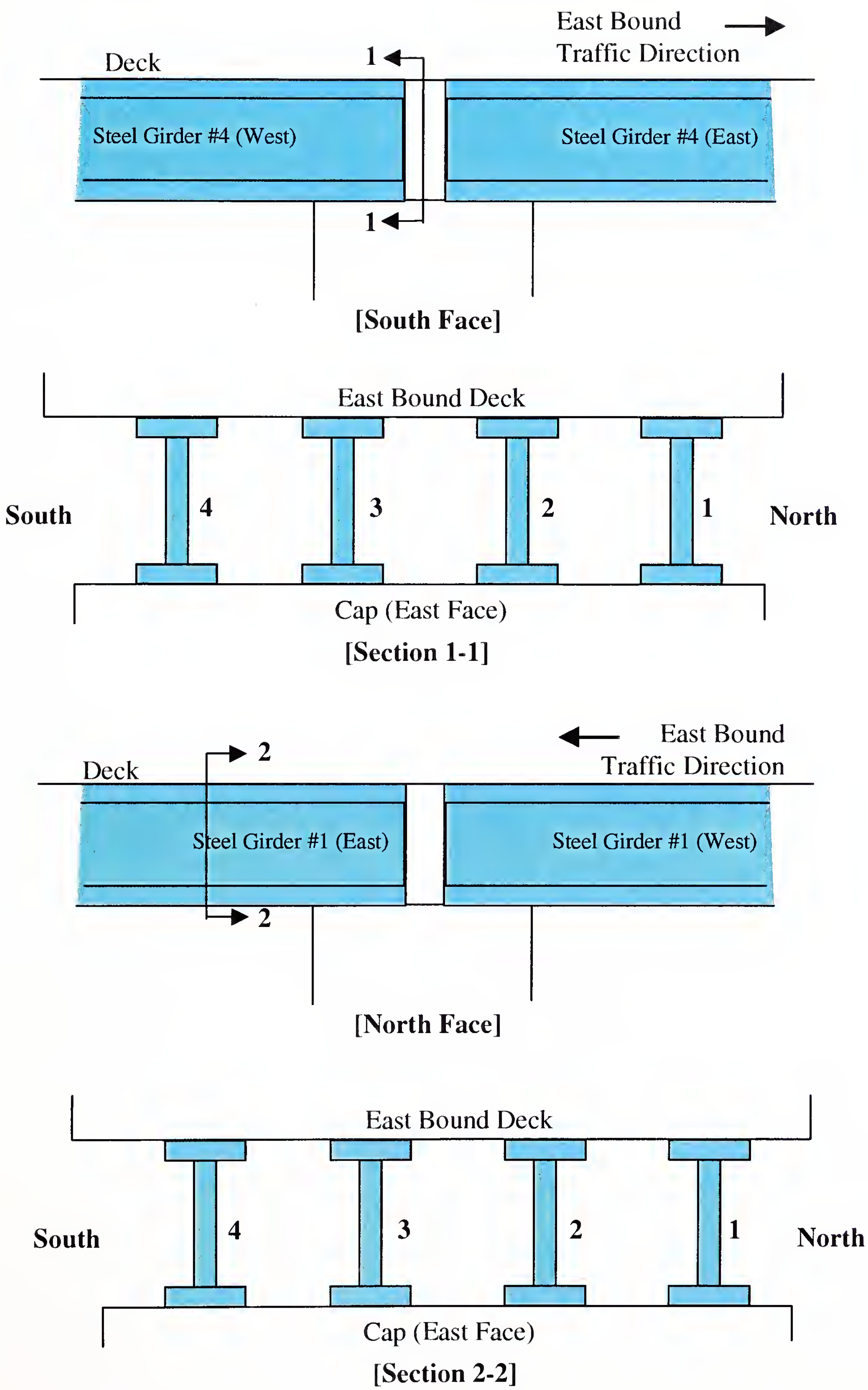


Figure 11B. Condition of Girder Joints over Bent No. 12 (East Bound).

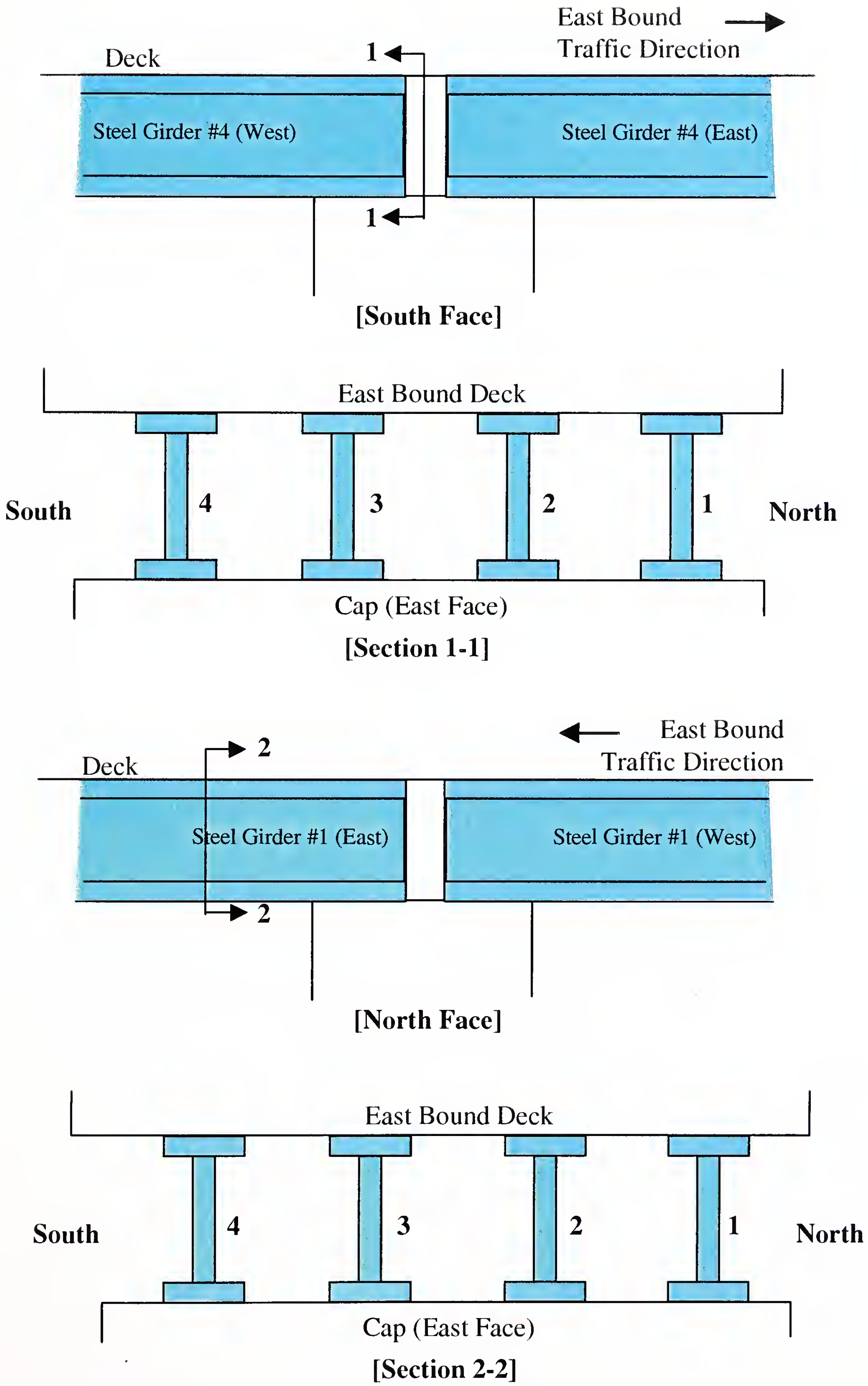


Figure 12B. Condition of Girder Joints over Bent No. 13 (East Bound).

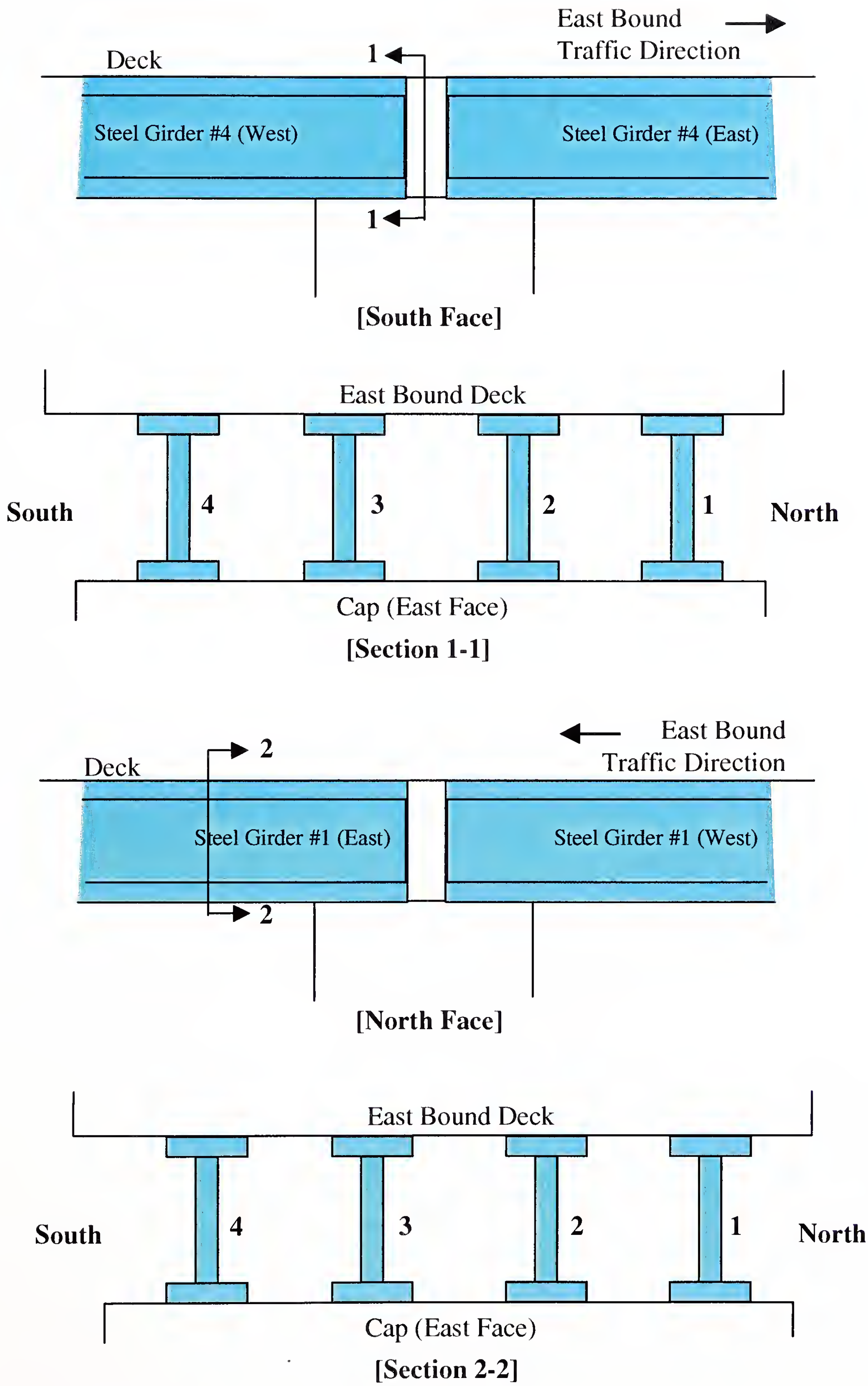


Figure 13B. Condition of Girder Joints over Bent No. 14 (East Bound).

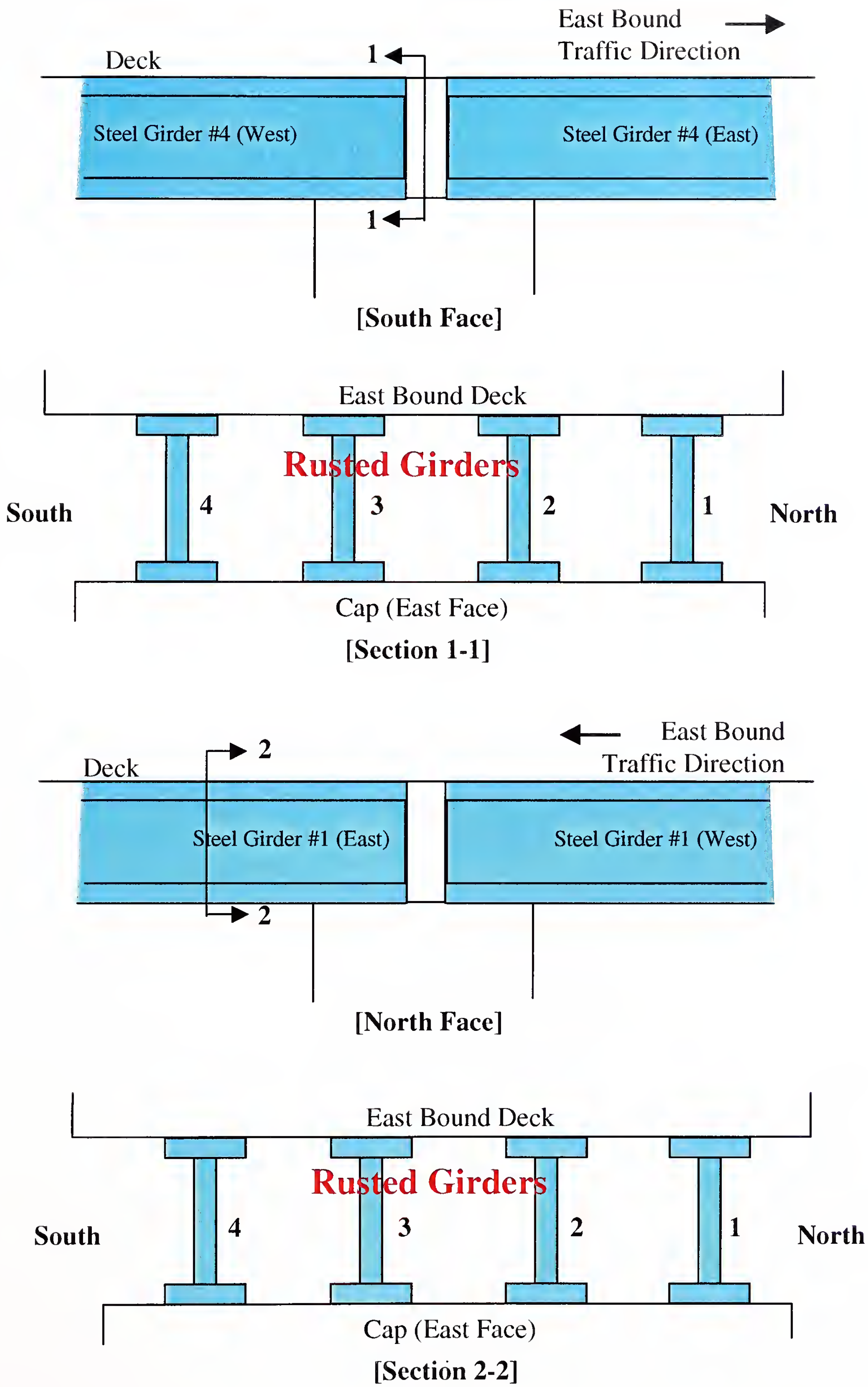


Figure 14B. Condition of Girder Joints over Bent No. 15 (East Bound).

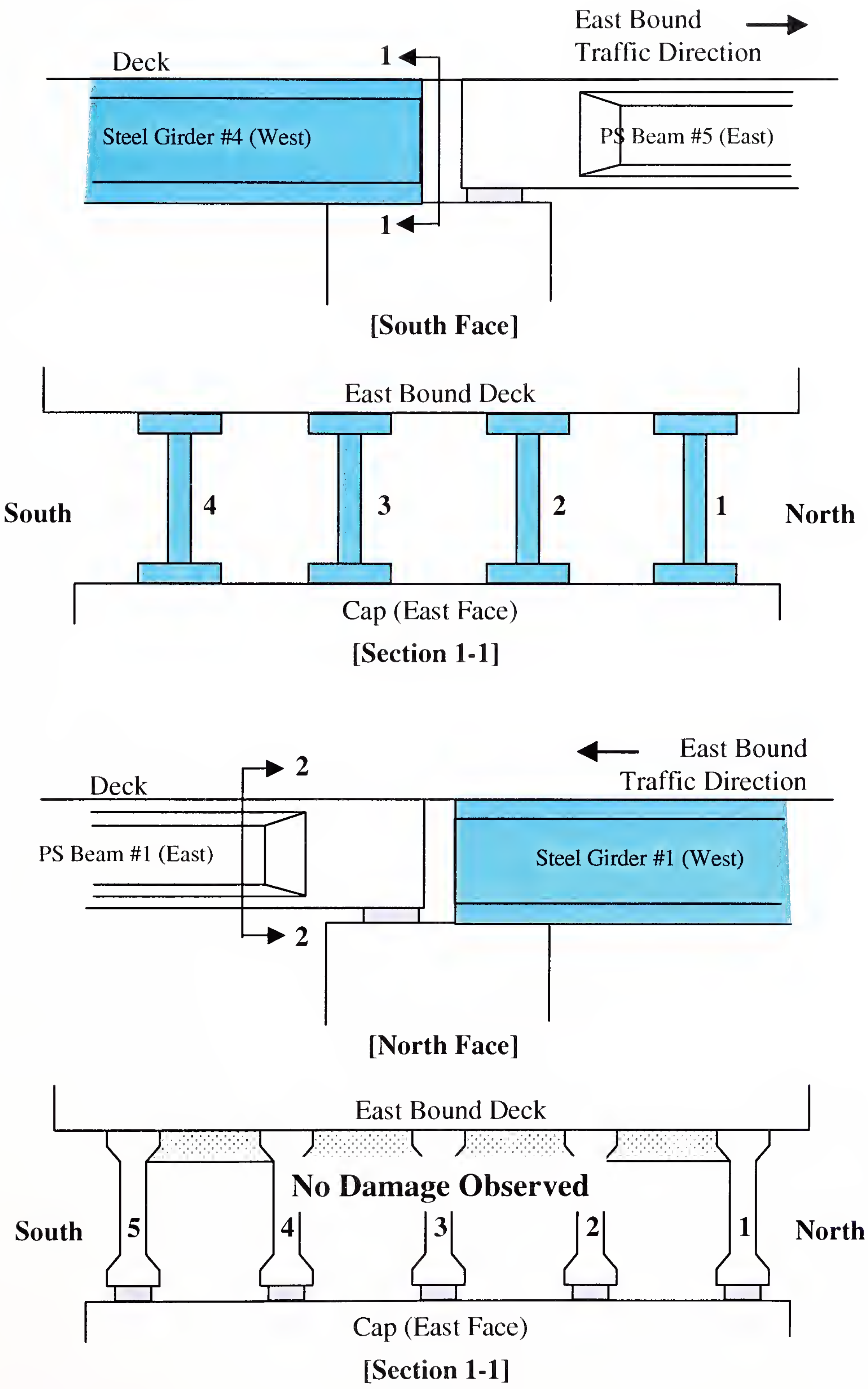


Figure 15B. Condition of Beam Joints over Bent No. 16 (East Bound).

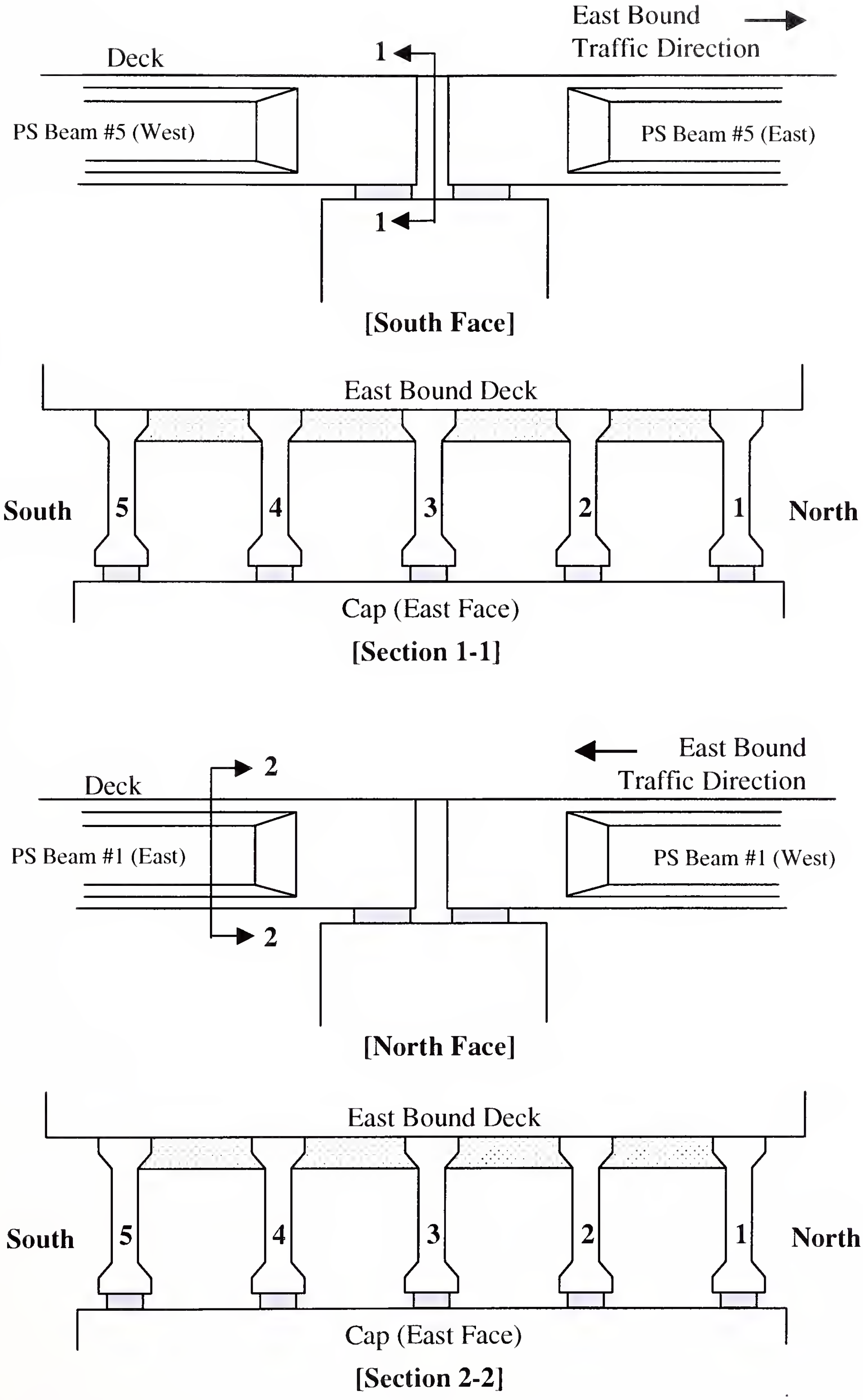
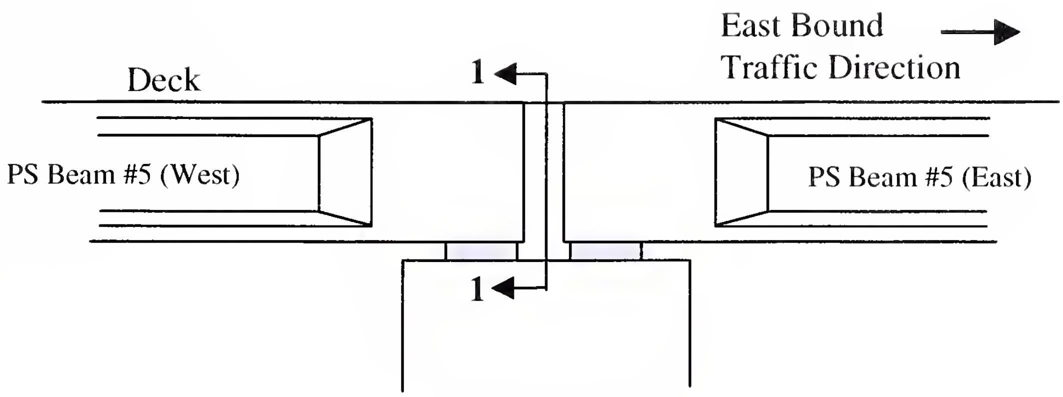
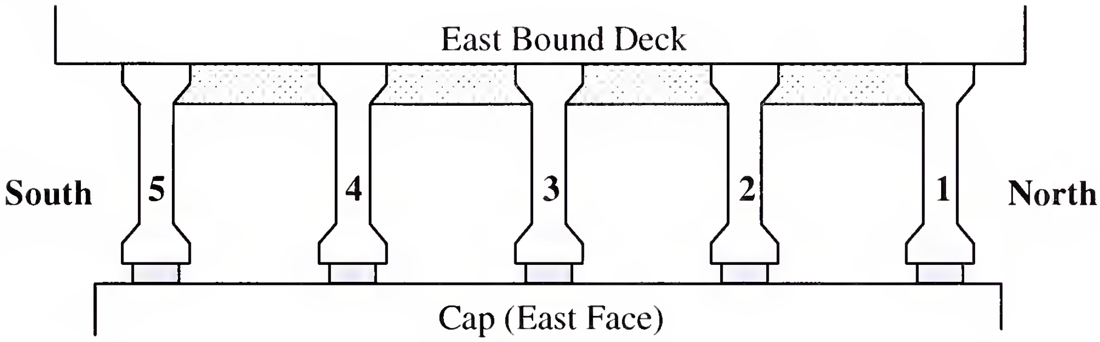


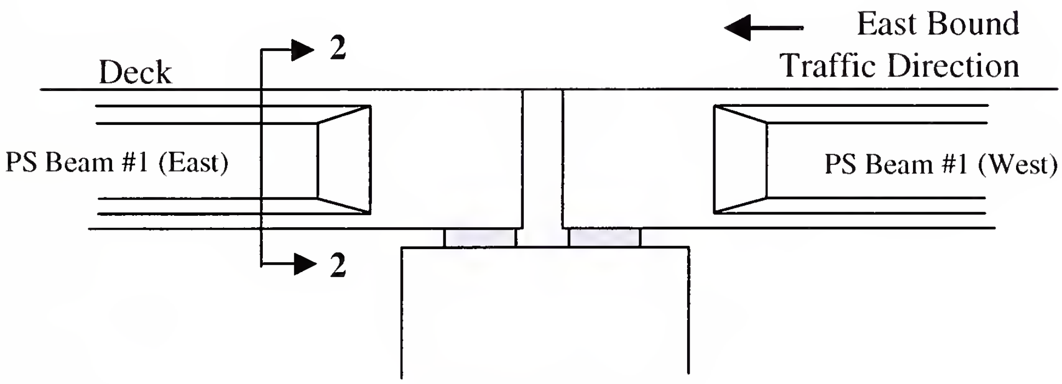
Figure 16B. Condition of Beam Joints over Bent No.17 (East Bound).



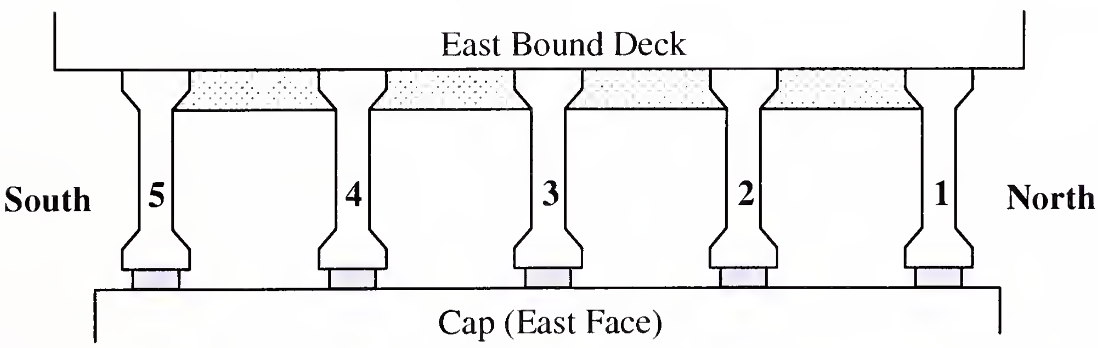
[South Face]



[Section 1-1]



[North Face]



[Section 2-2]

Figure 17B. Condition of Beam Joints over Bent No.18 (East Bound).

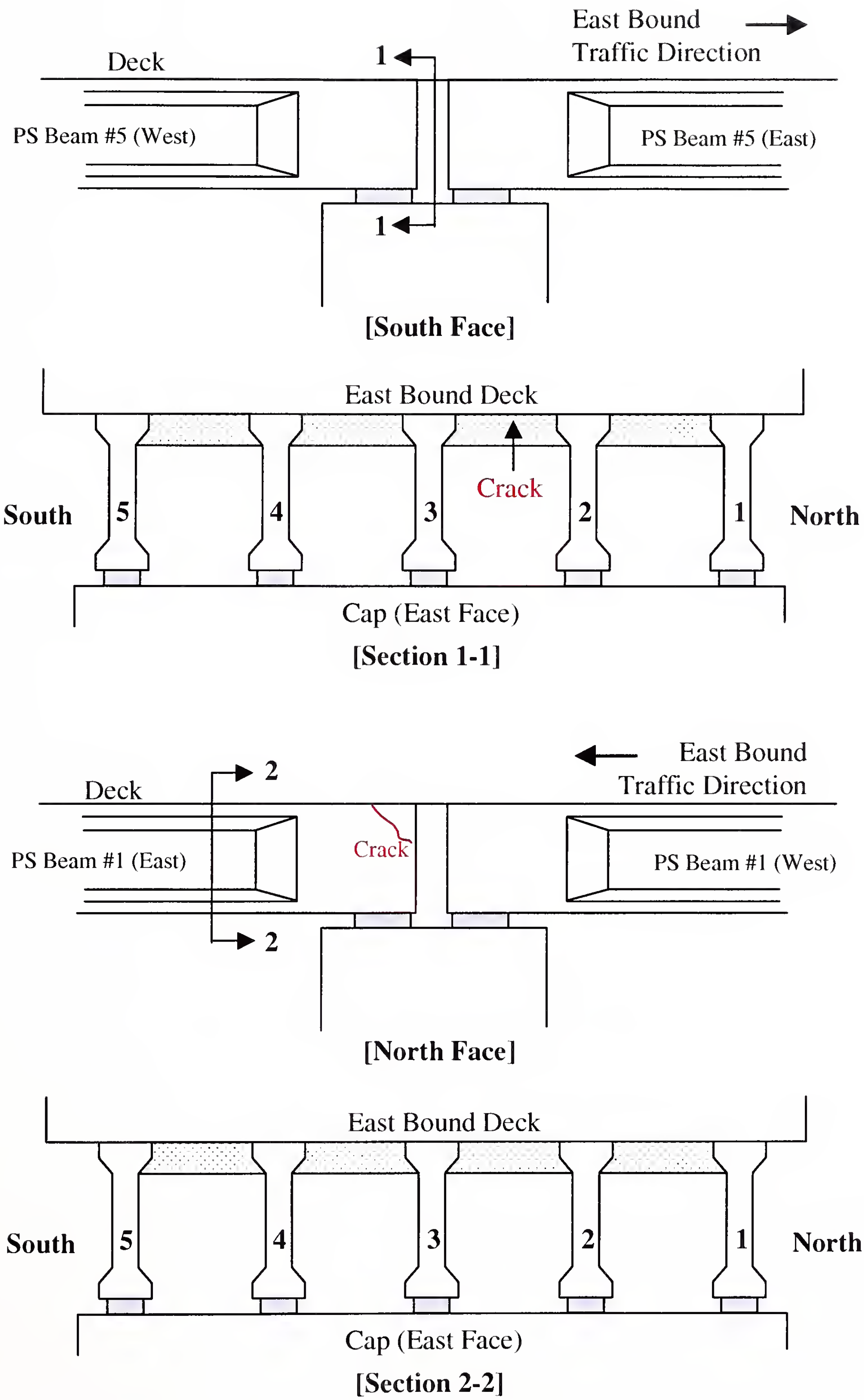


Figure 18B. Condition of Beam Joints over Bent No. 19 (East Bound).

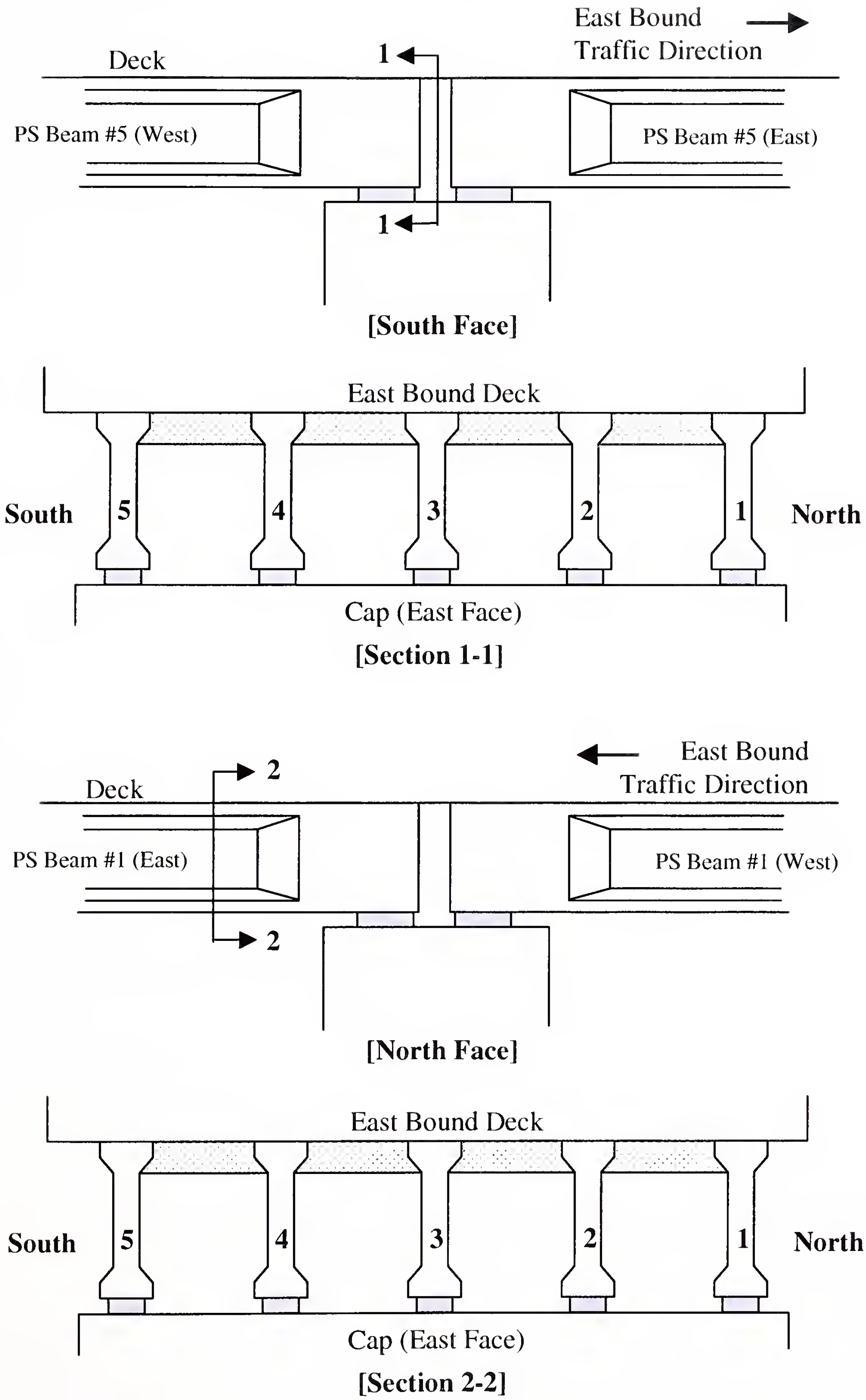


Figure 19B. Condition of Beam Joints over Bent No.20 (East Bound).

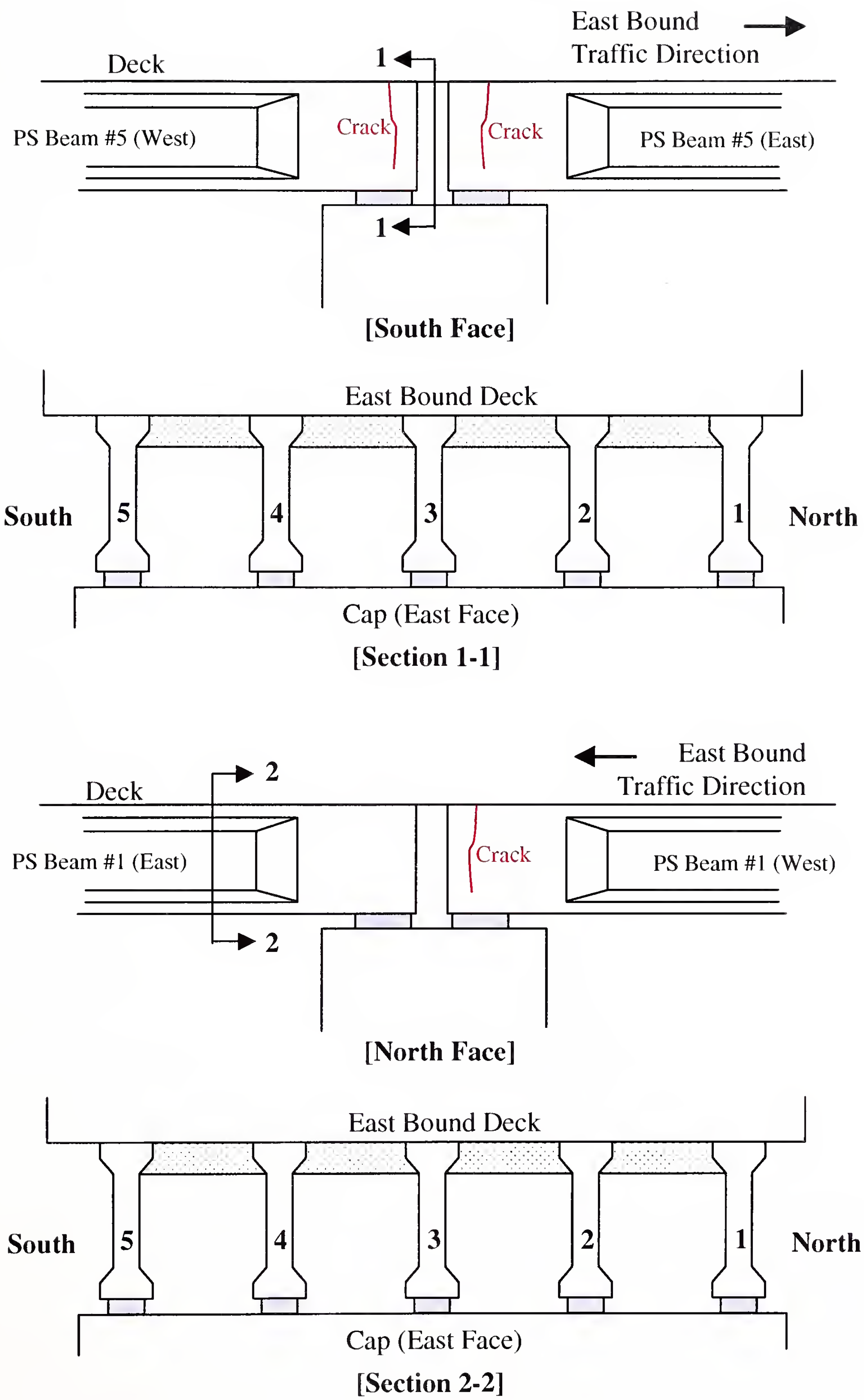


Figure 20B. Condition of Beam Joints over Bent No. 21 (East Bound).

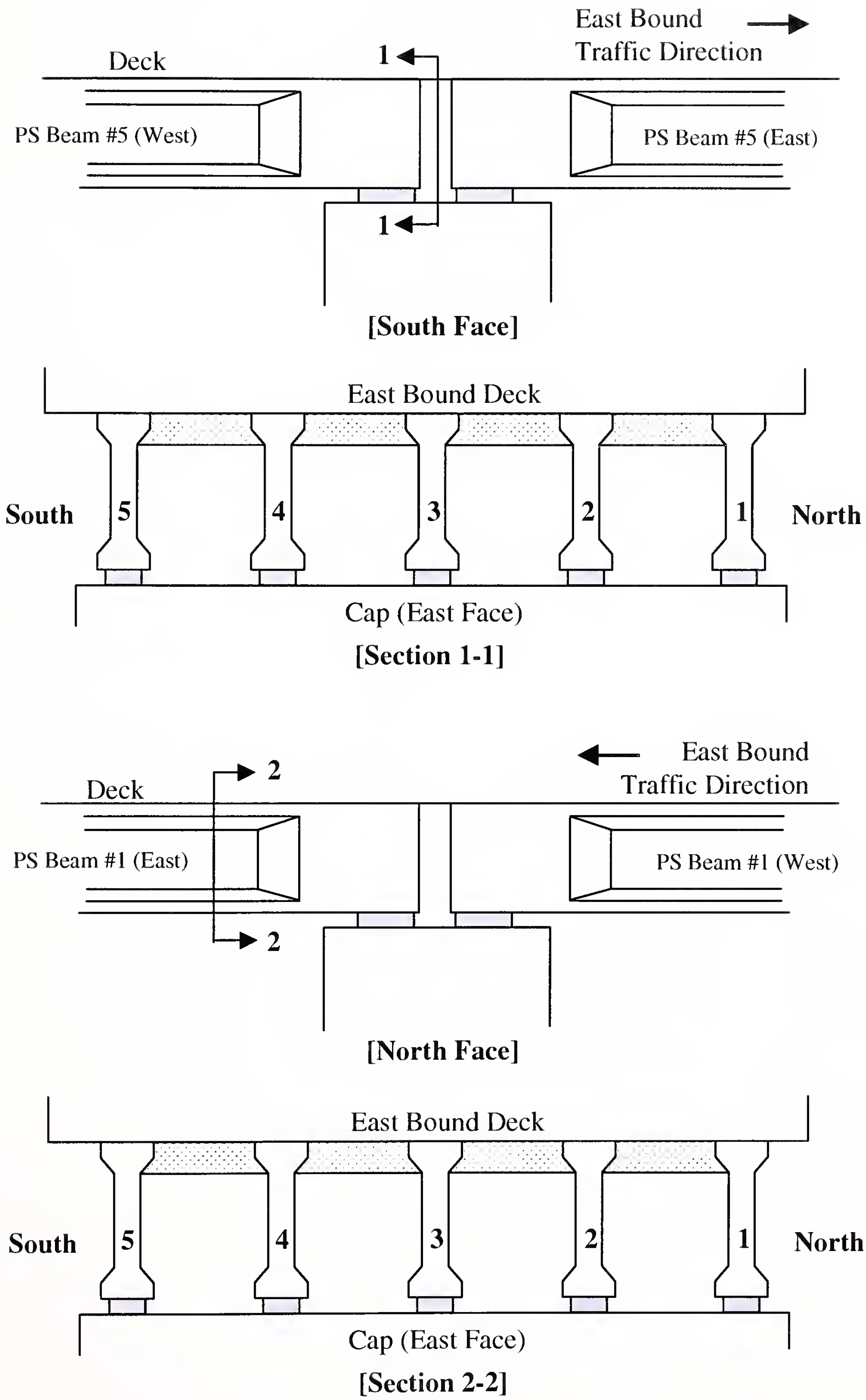


Figure 21B. Condition of Beam Joints over Bent No.22 (East Bound).

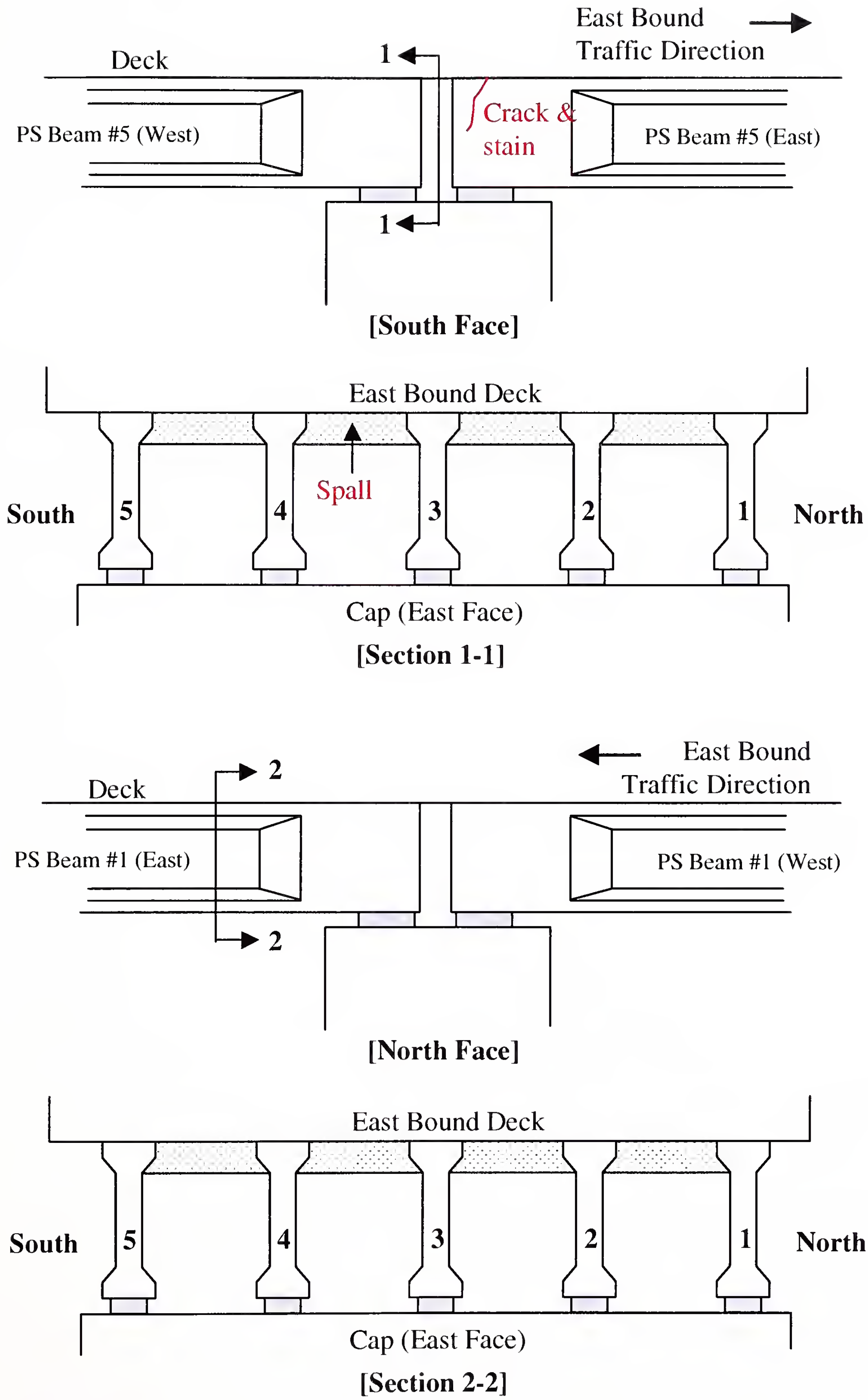


Figure 22B. Condition of Beam Joints over Bent No. 23 (East Bound).

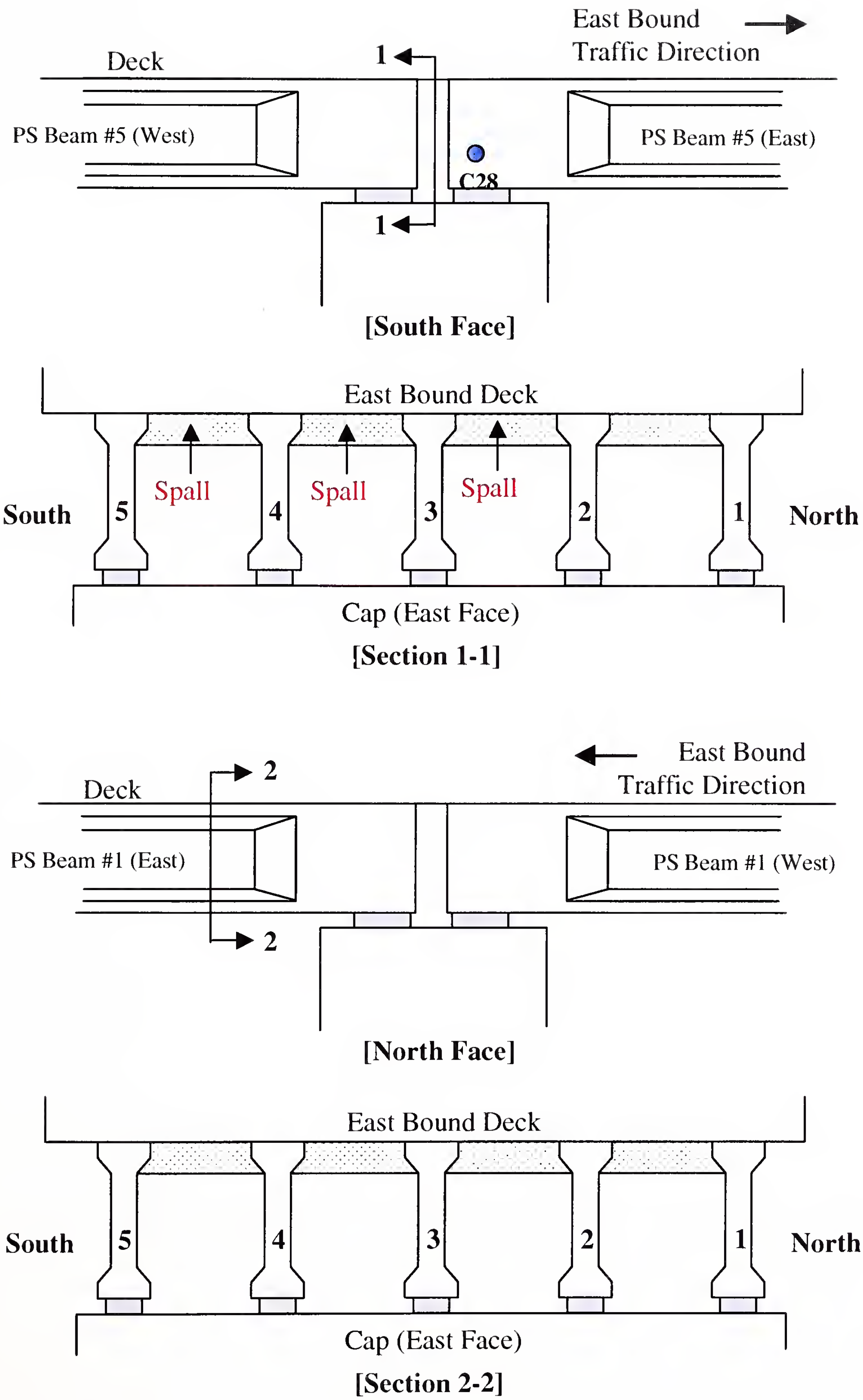


Figure 23B. Condition of Beam Joints over Bent No. 24 (East Bound).

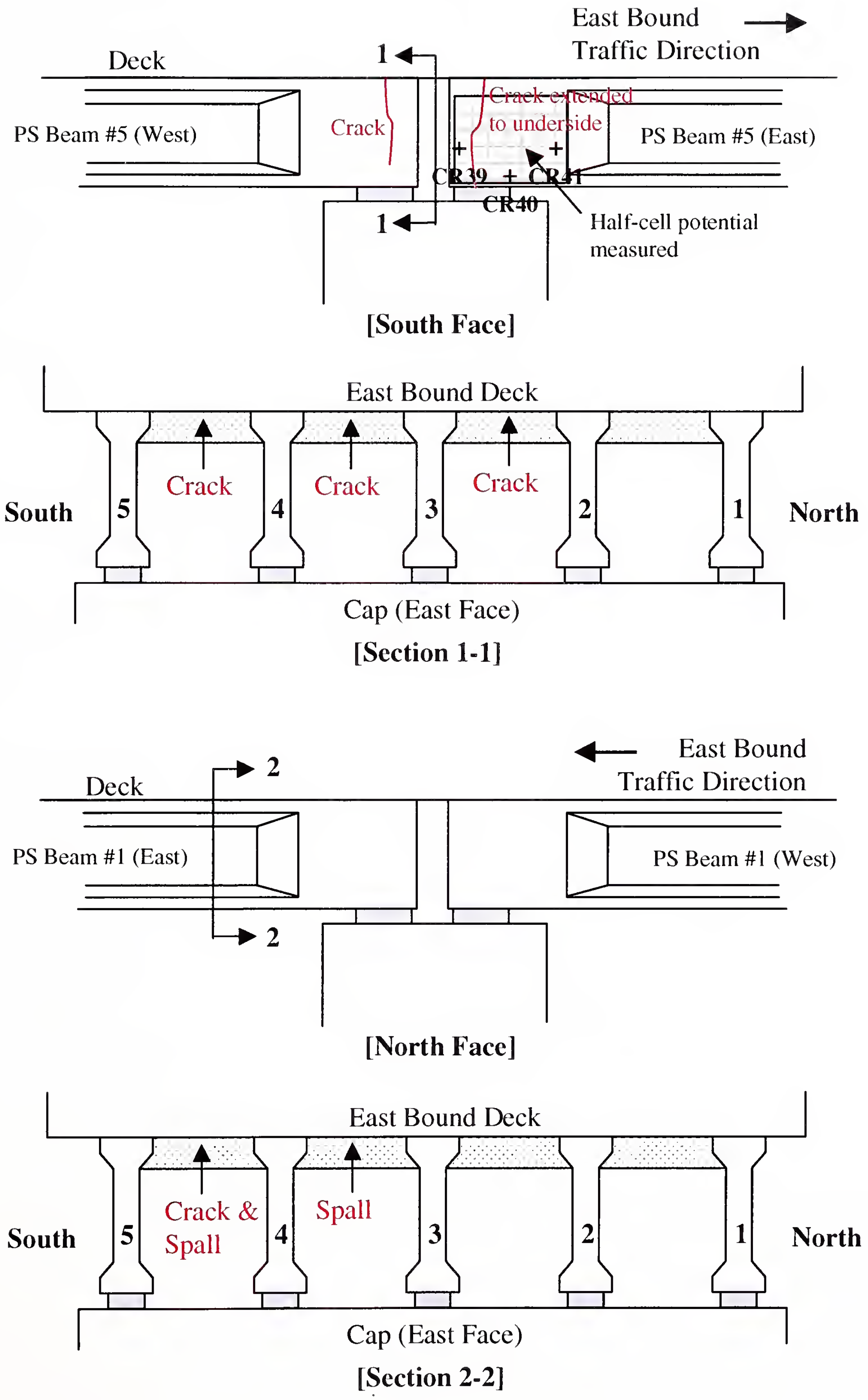


Figure 24B. Condition of Beam Joints over Bent No. 25 (East Bound).

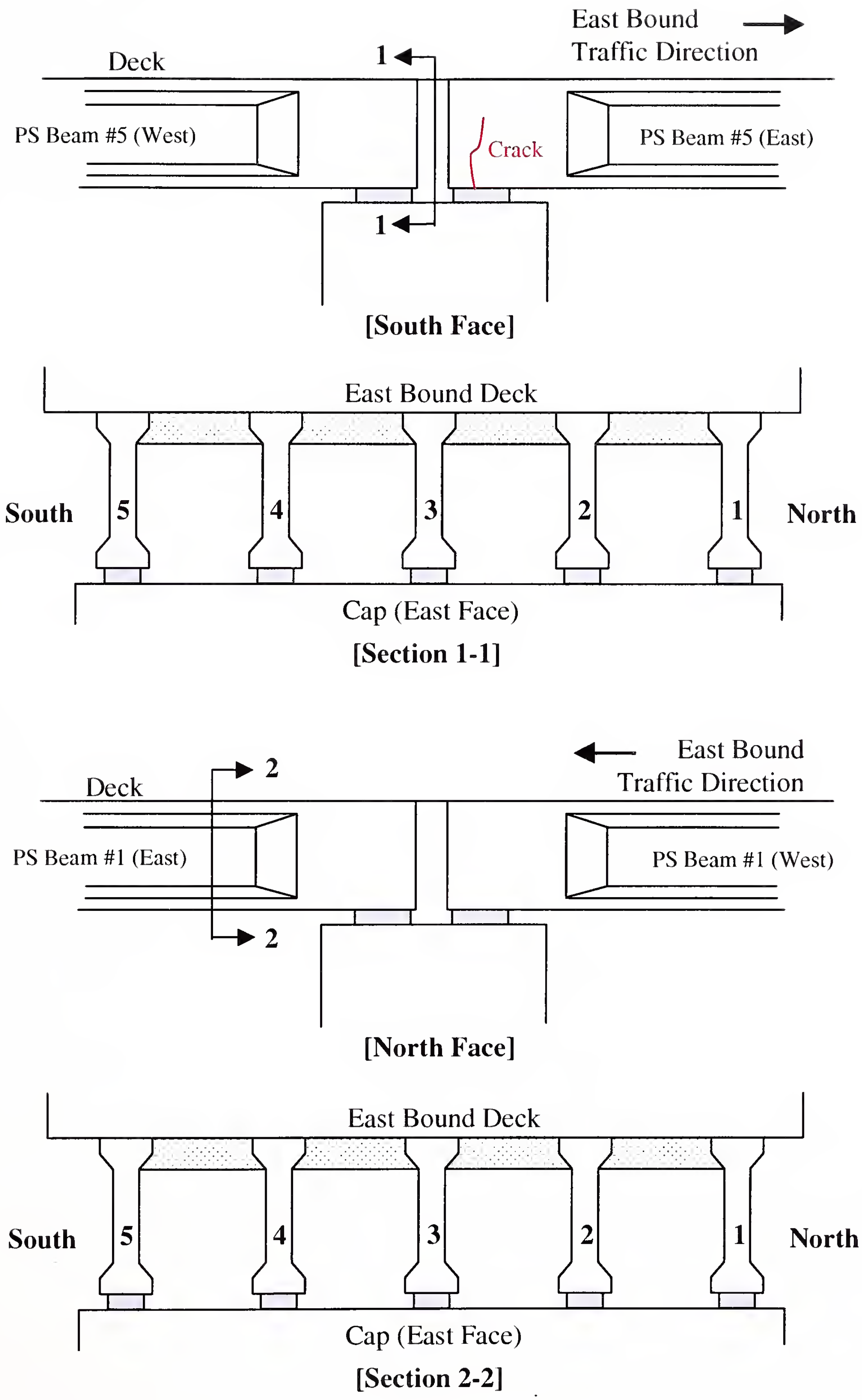


Figure 25B. Condition of Beam Joints over Bent No. 26 (East Bound).

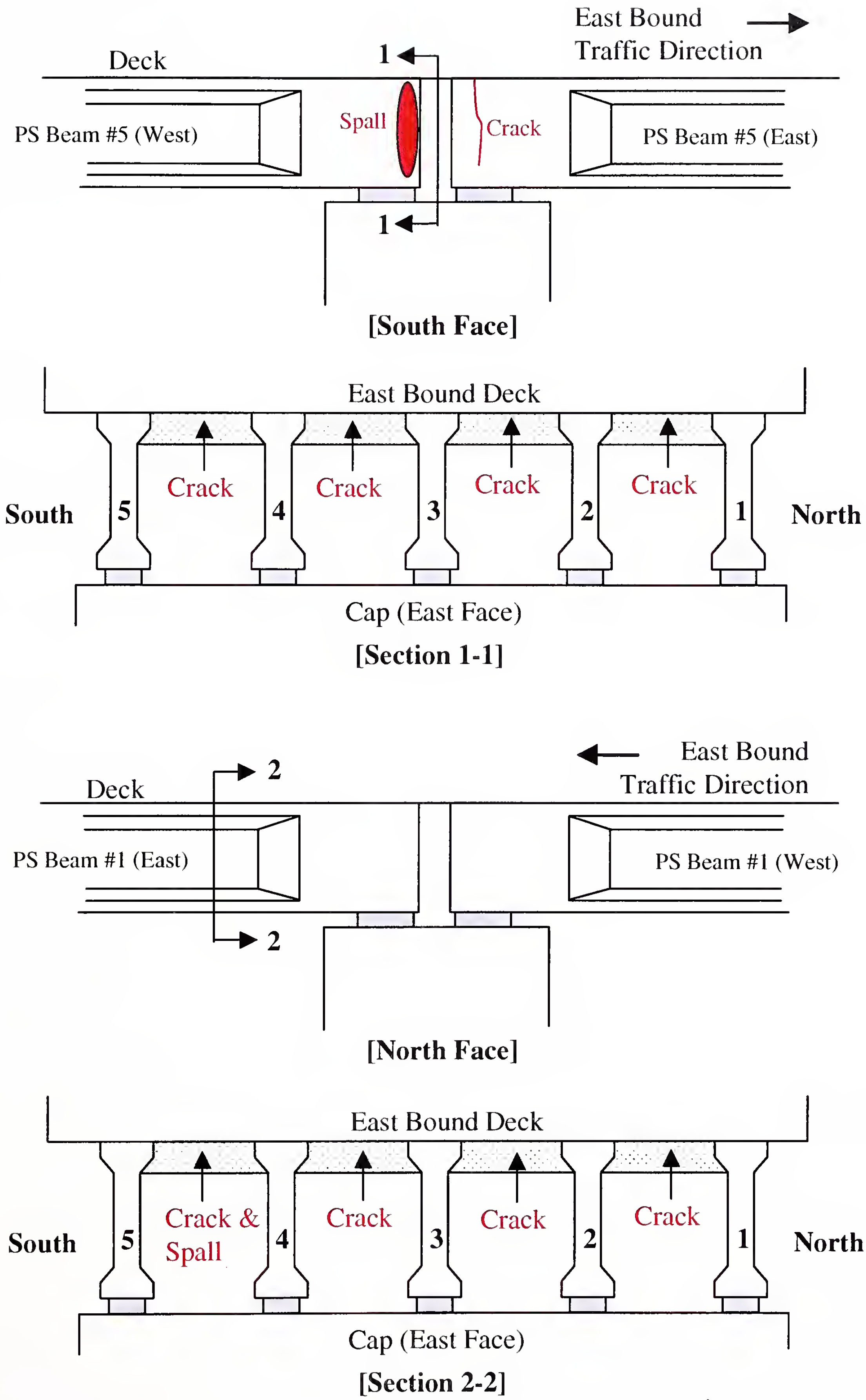


Figure 26B. Condition of Beam Joints over Bent No. 27 (East Bound).

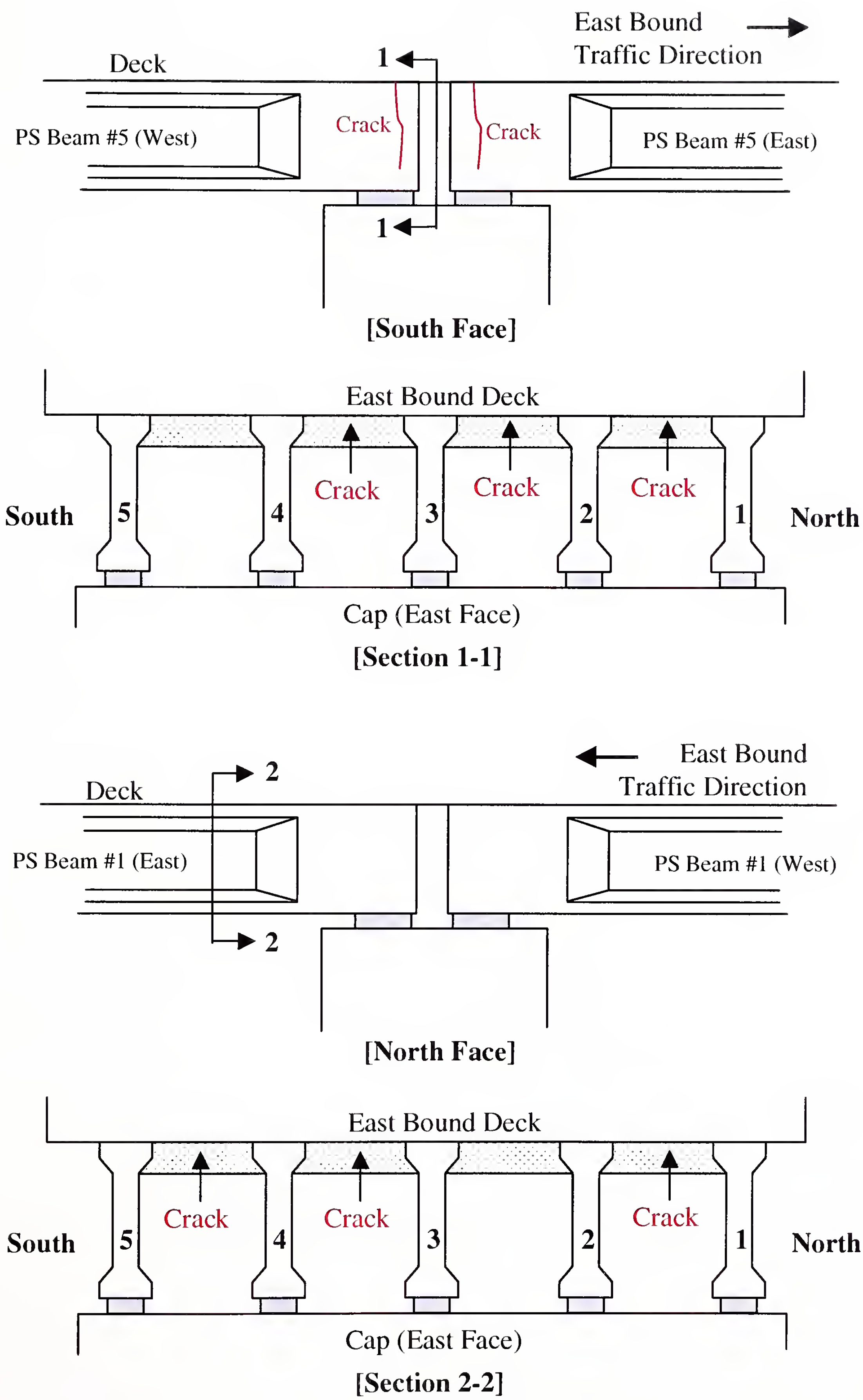


Figure 27B. Condition of Beam Joints over Bent No. 28 (East Bound).

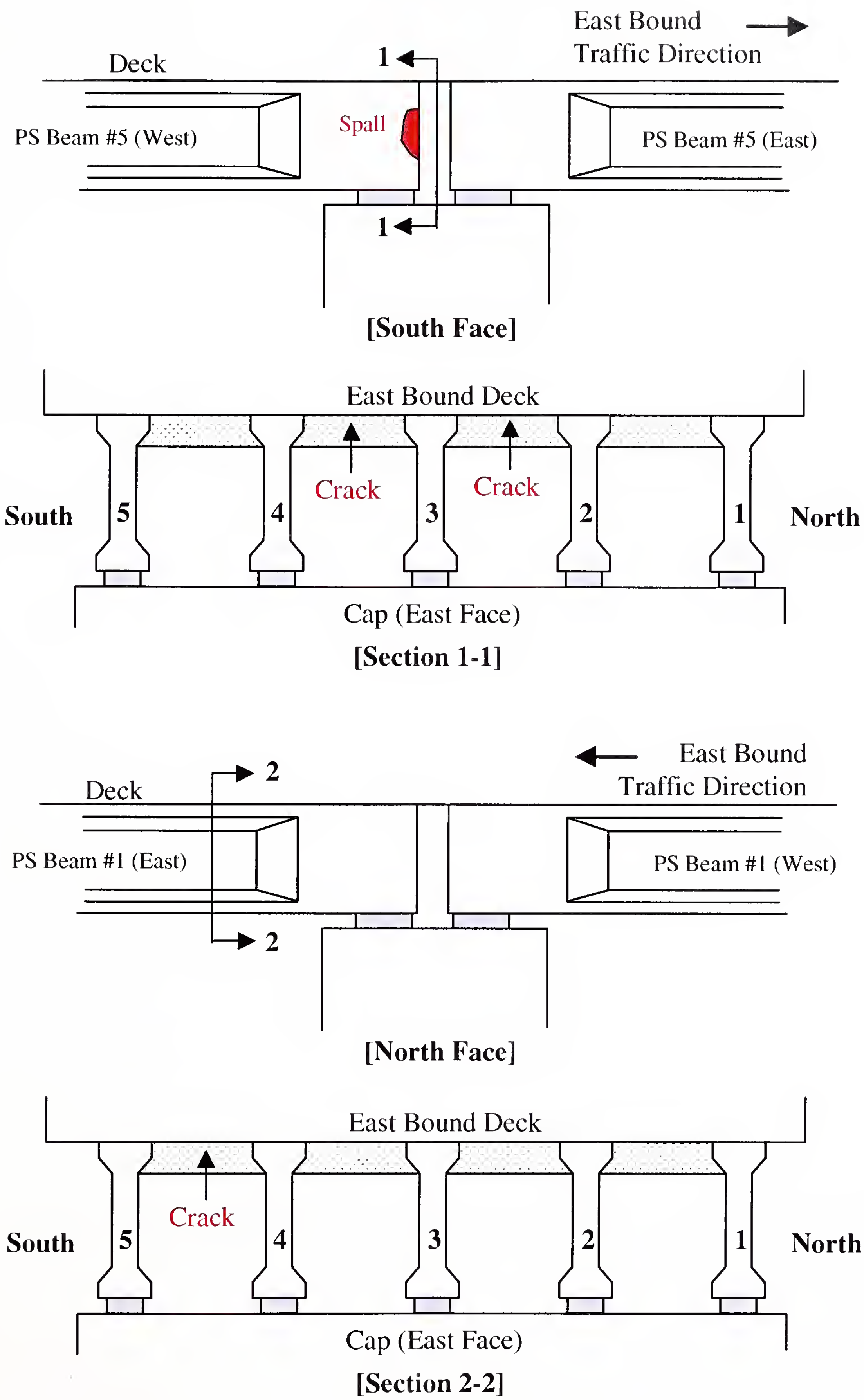


Figure 28B. Condition of Beam Joints over Bent No. 29 (East Bound).

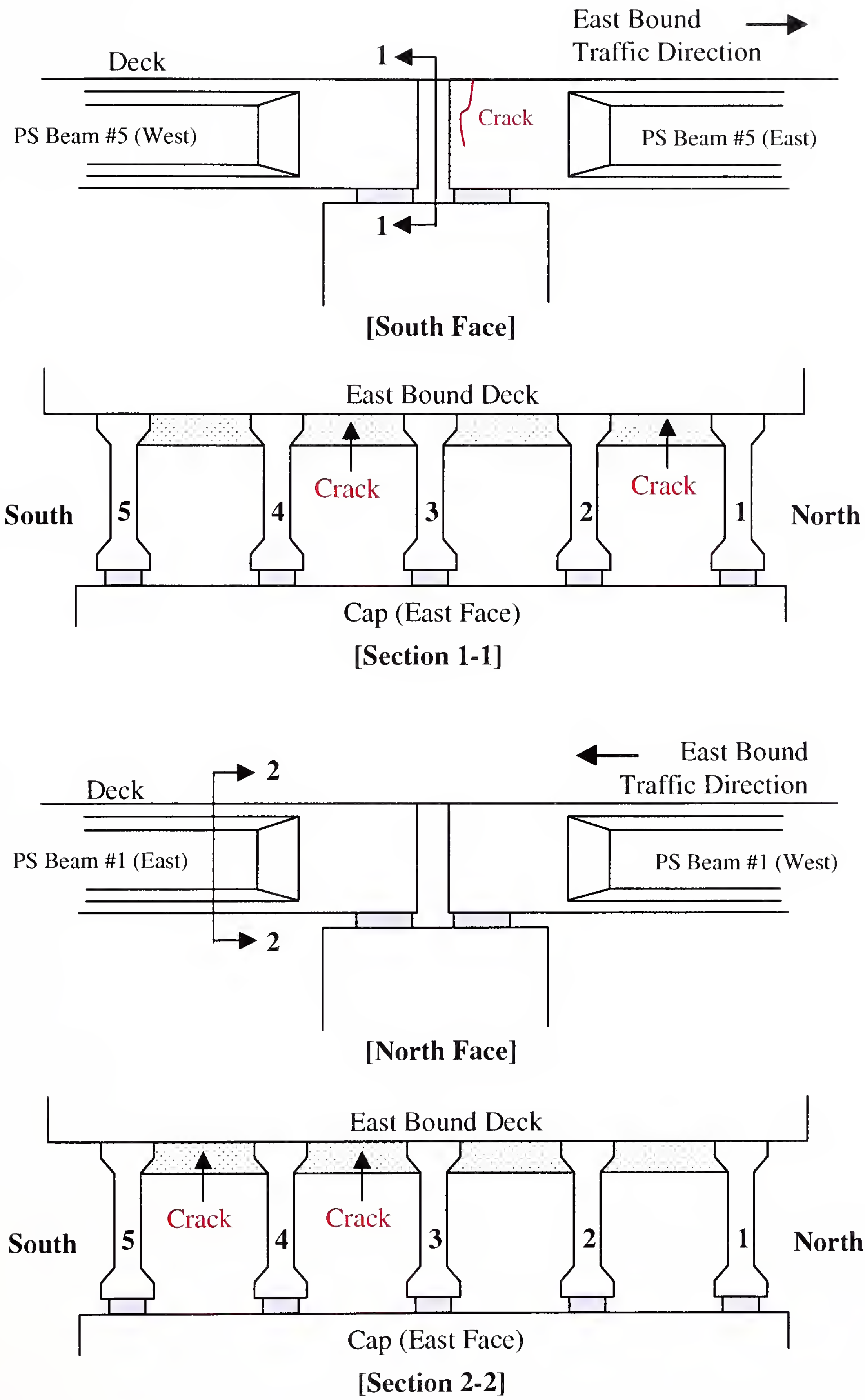


Figure 29B. Condition of Beam Joints over Bent No. 30 (East Bound).

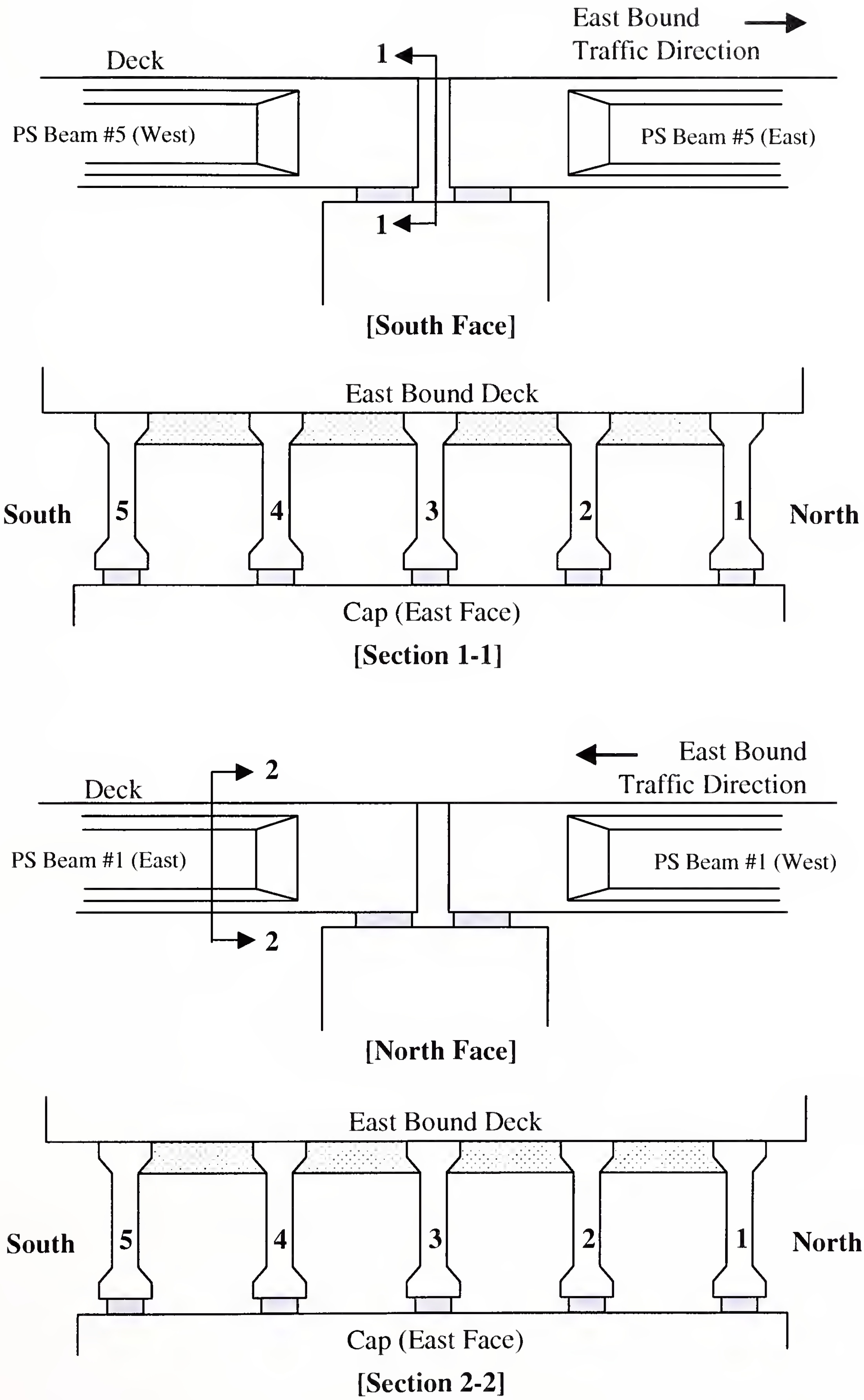


Figure 30B. Condition of Beam Joints over Bent No.31 (East Bound).

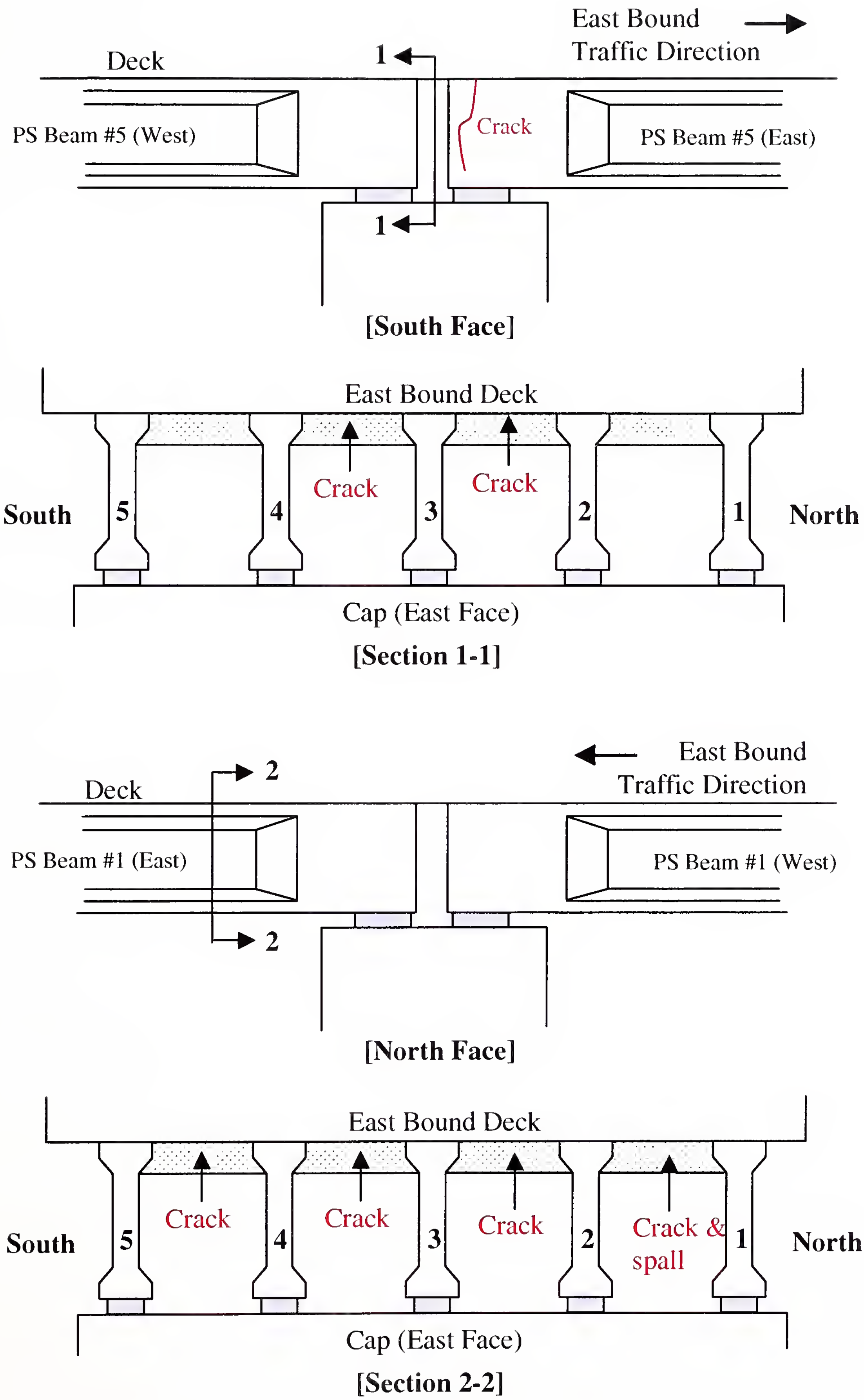


Figure 31B. Condition of Beam Joints over Bent No. 32 (East Bound).

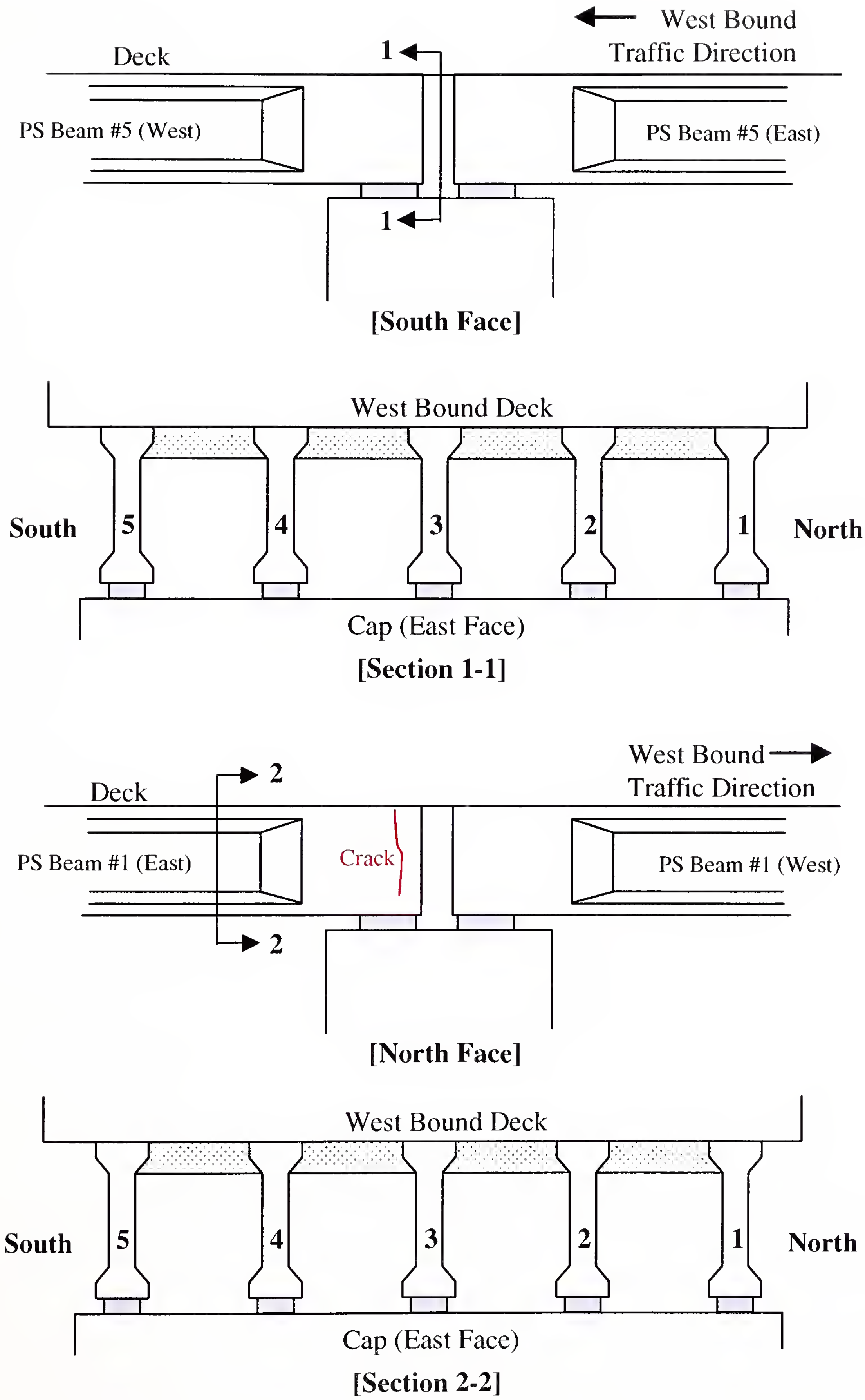


Figure 32B. Condition of Beam Joints over Bent No. 2 (West Bound).

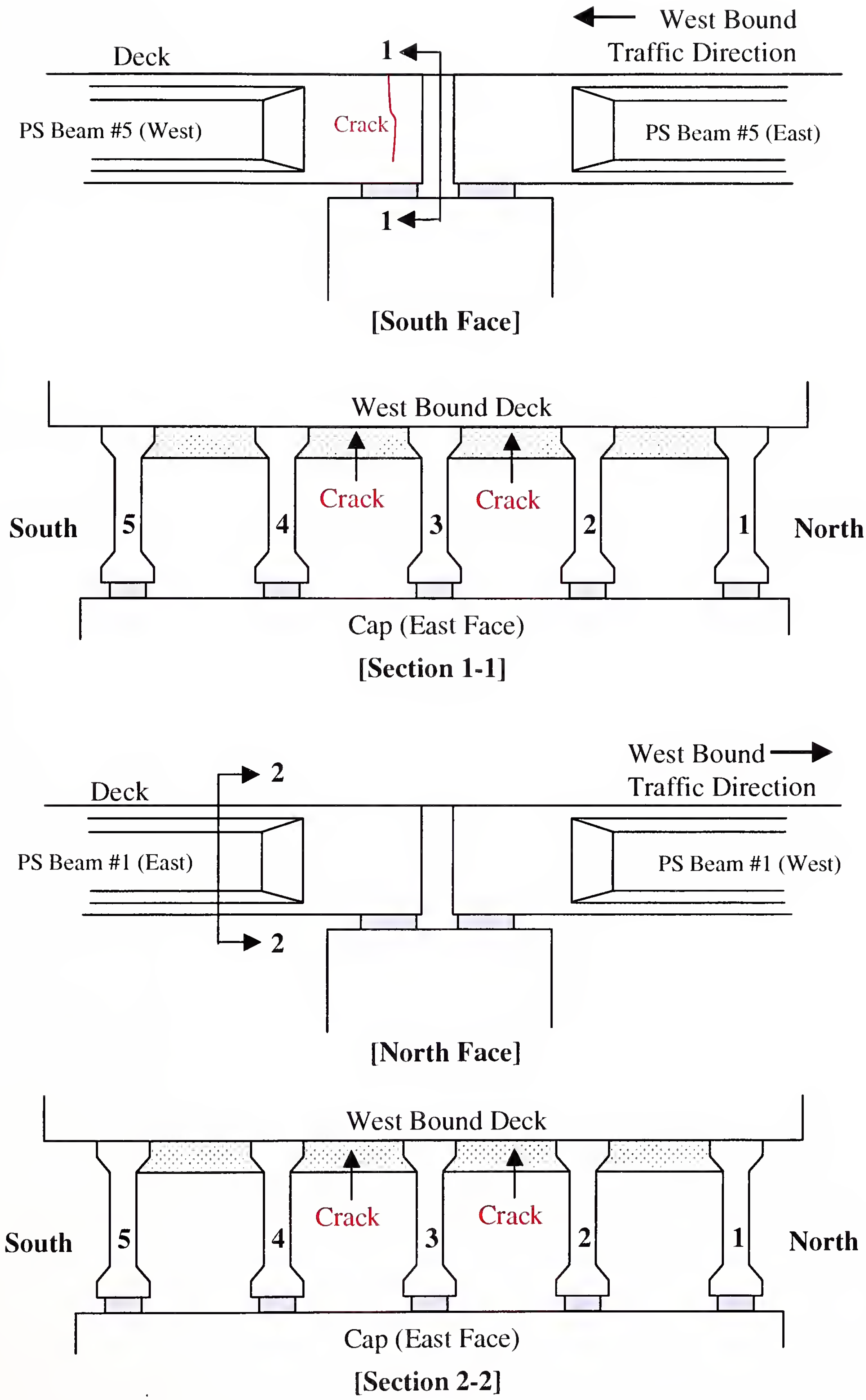


Figure 33B. Condition of Beam Joints over Bent No. 3 (West Bound).

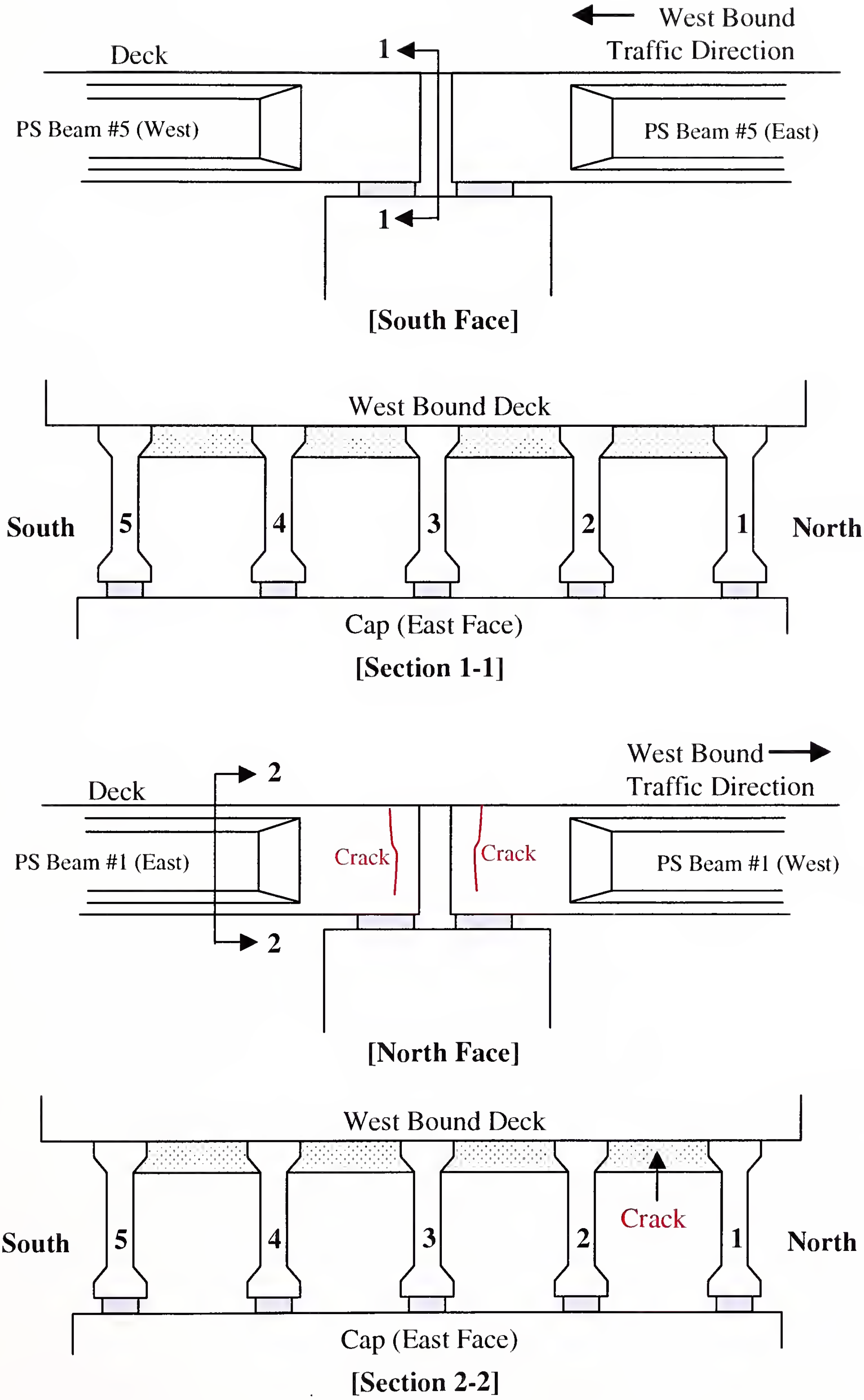


Figure 34B. Condition of Beam Joints over Bent No. 4 (West Bound).

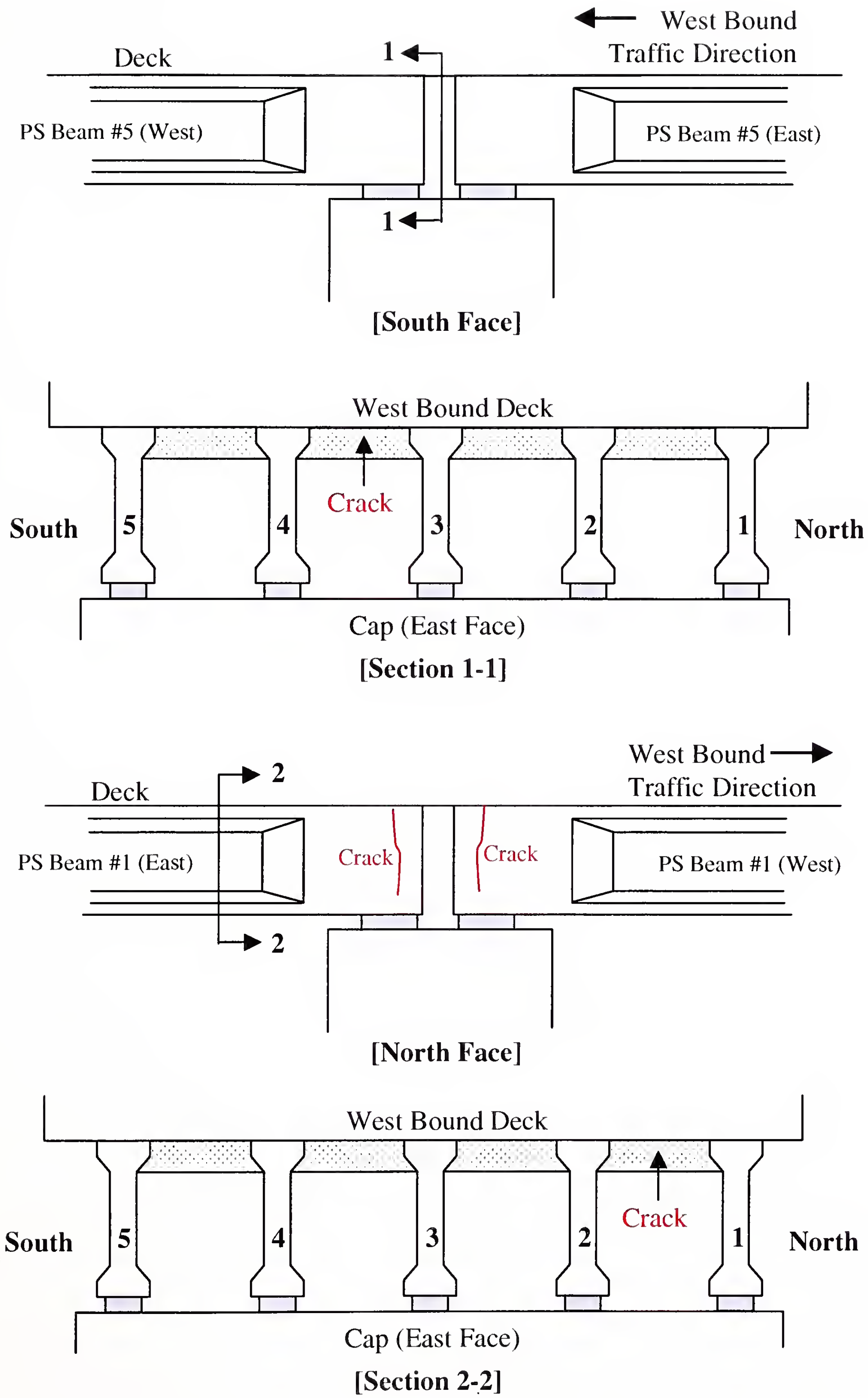


Figure 35B. Condition of Beam Joints over Bent No. 5 (West Bound).

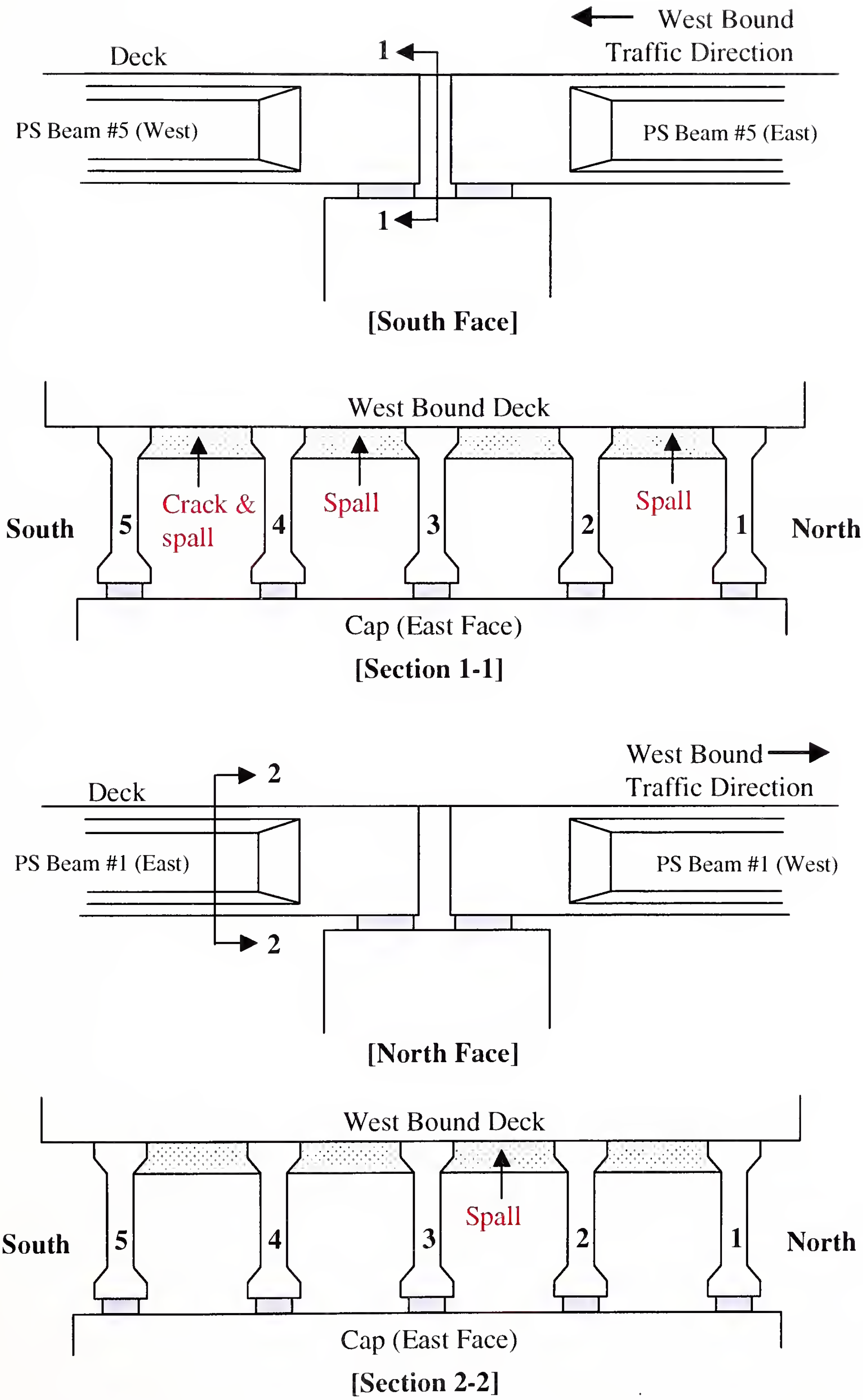


Figure 36B. Condition of Beam Joints over Bent No. 6 (West Bound).

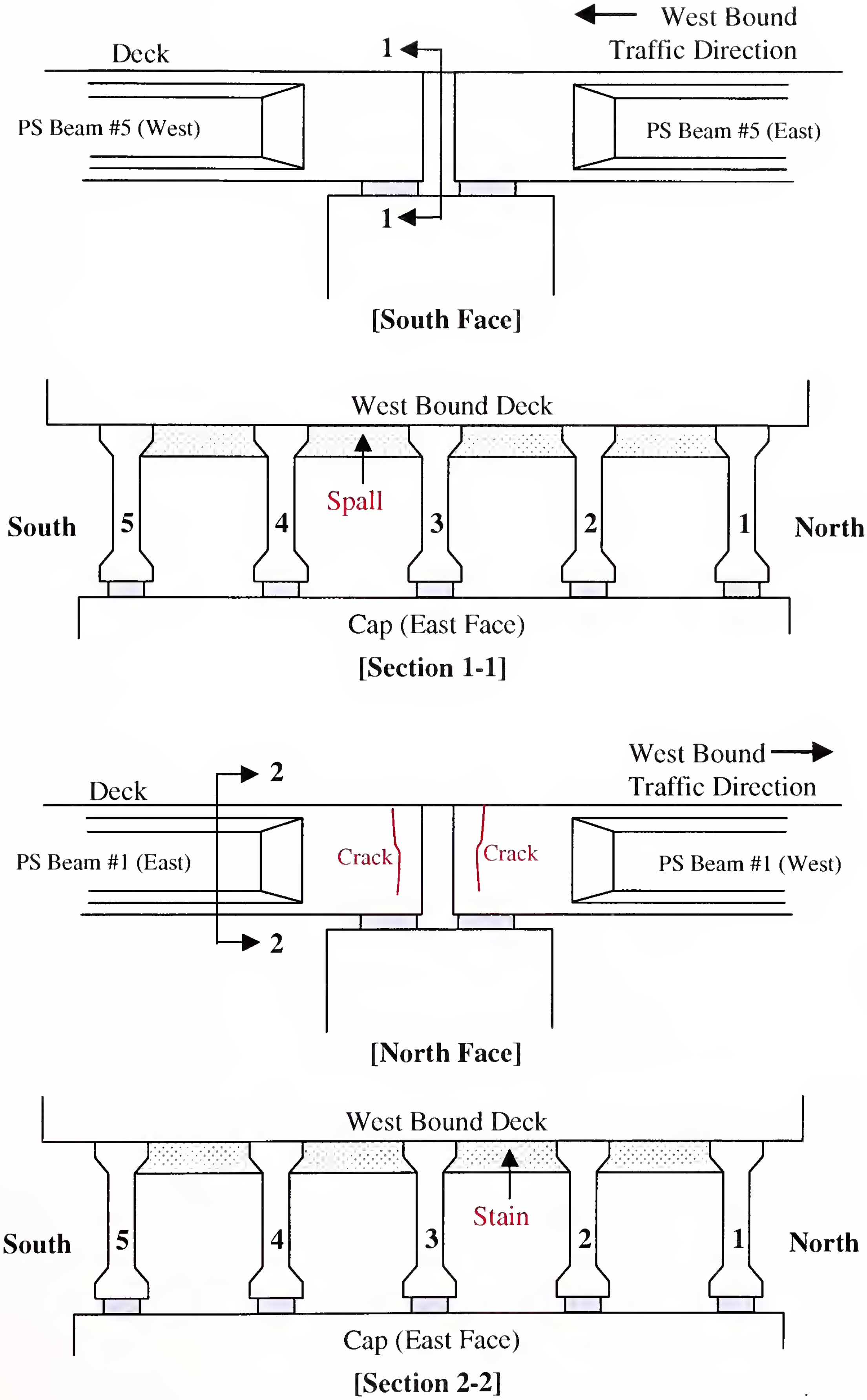


Figure 37B. Condition of Beam Joints over Bent No. 7 (West Bound).

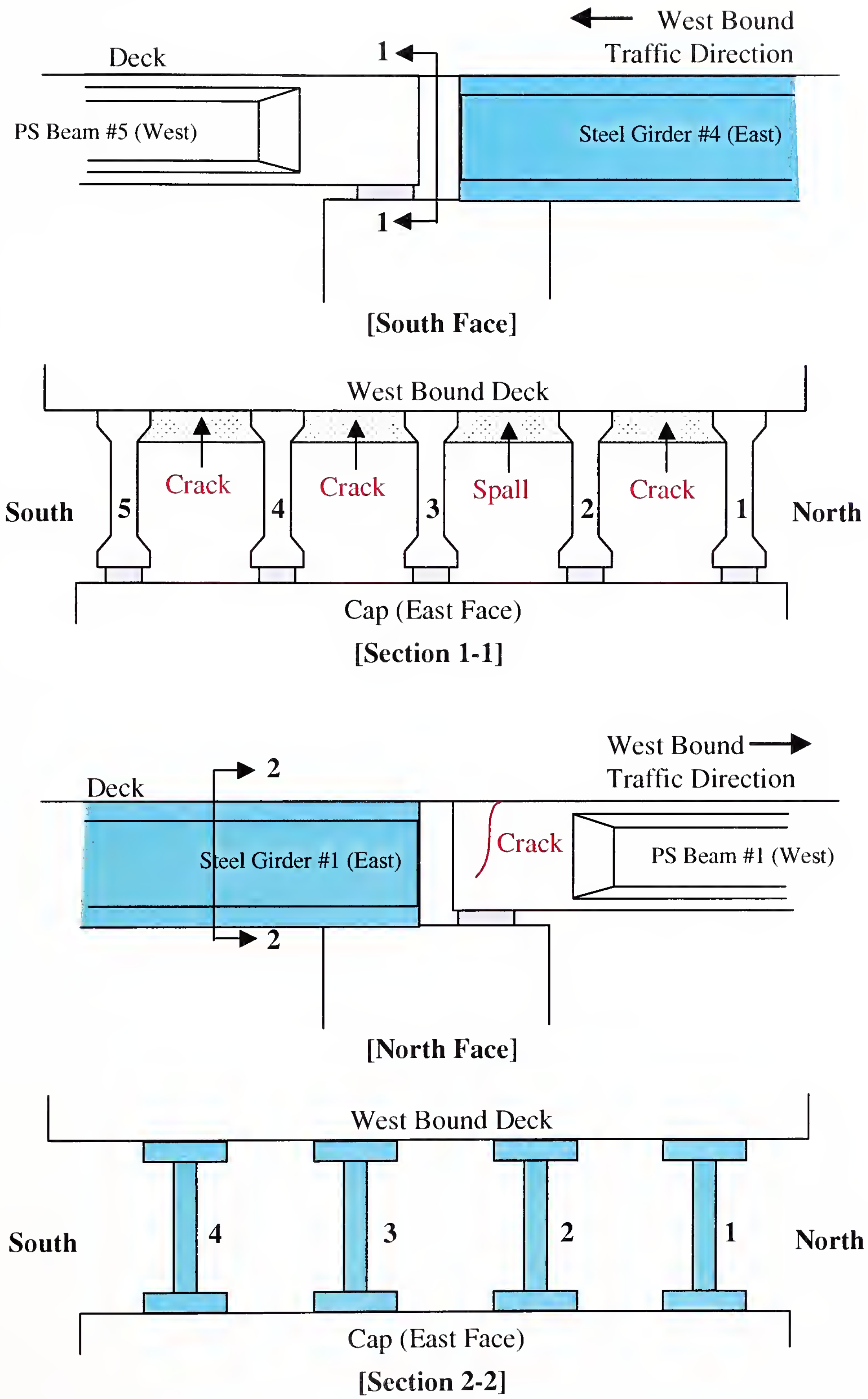


Figure 38B. Condition of Beam Joints over Bent No. 8 (West Bound).

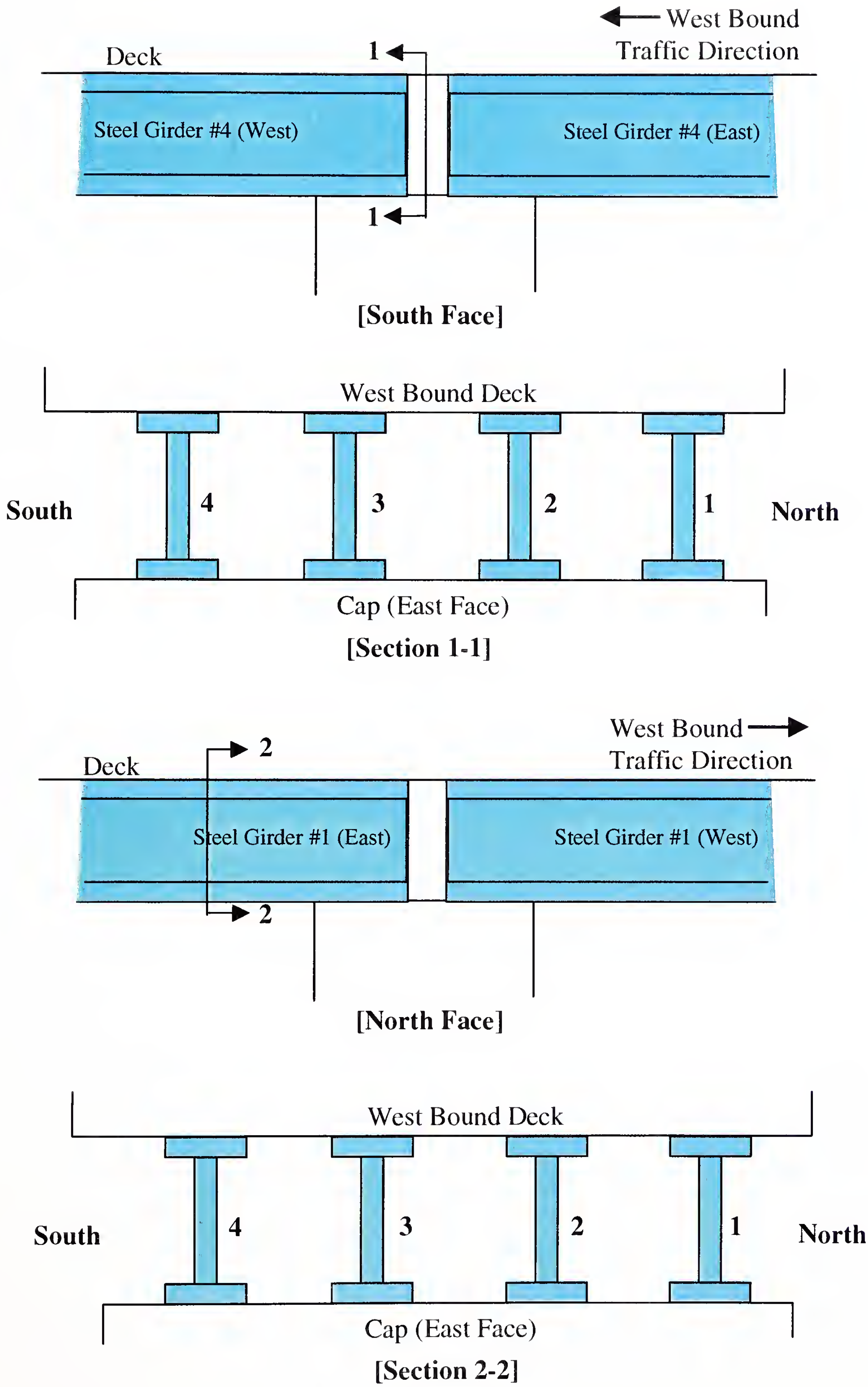


Figure 39B. Condition of Girder Joints over Bent No. 9 (West Bound).

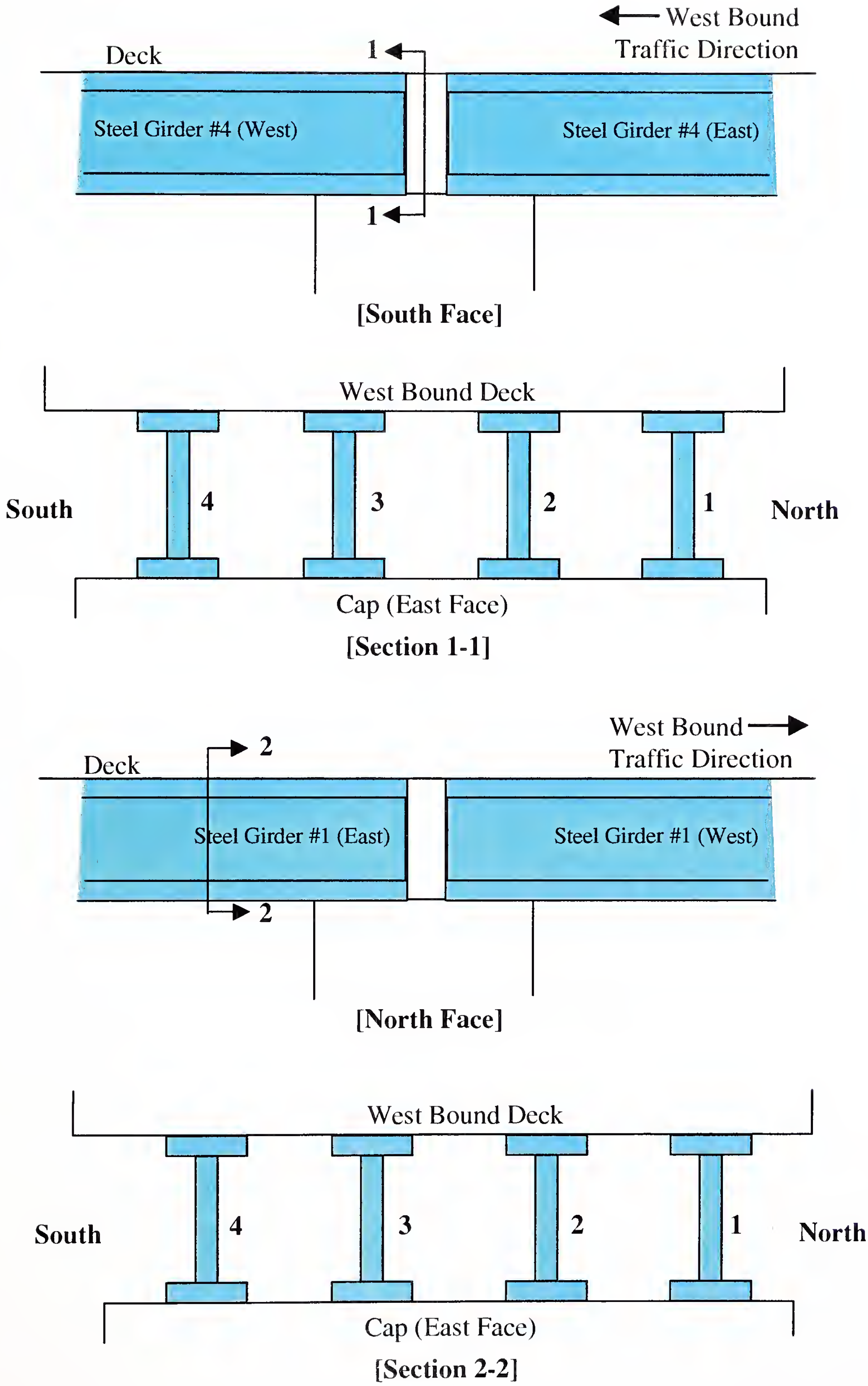


Figure 40B. Condition of Girder Joints over Bent No. 10 (West Bound).

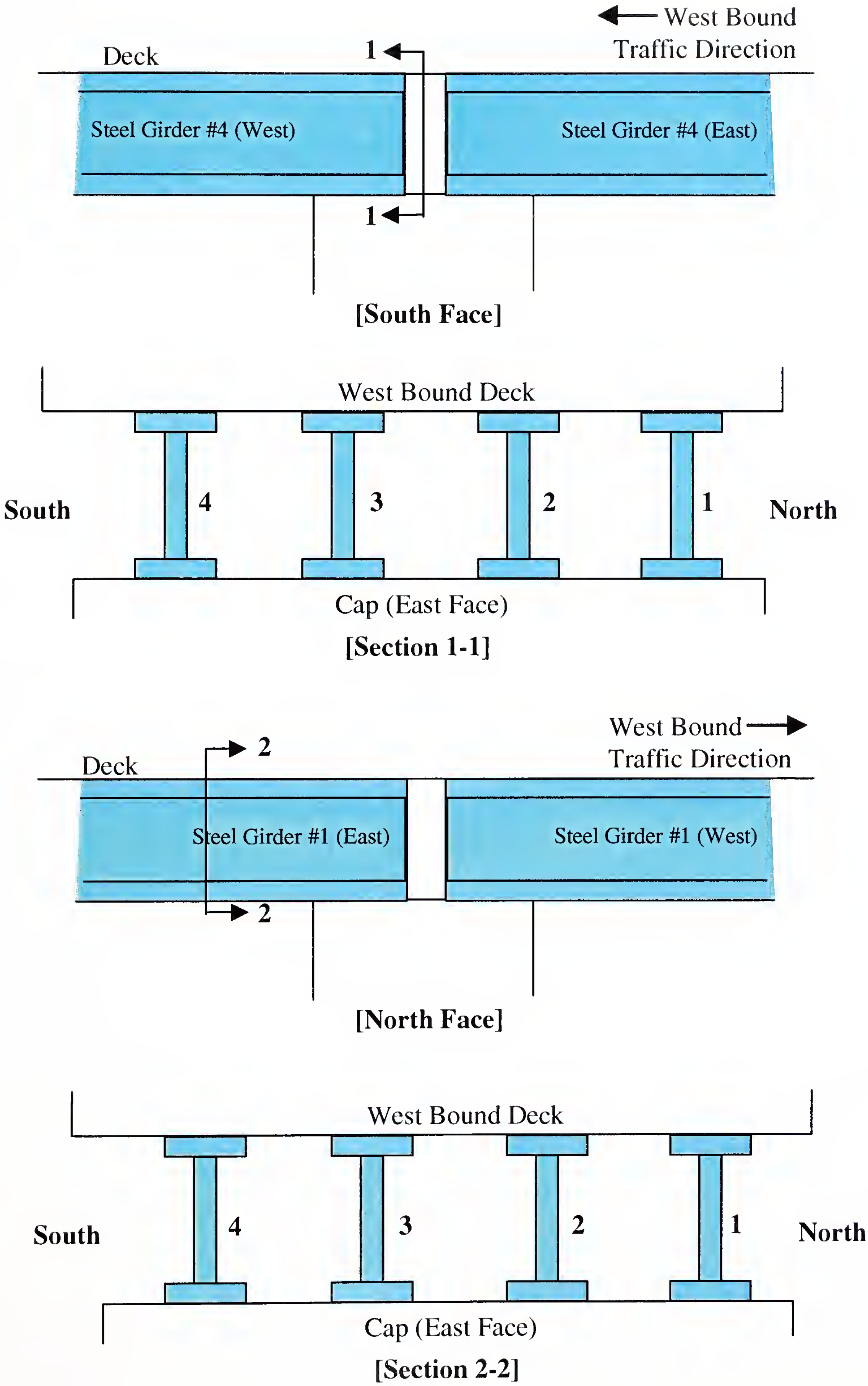


Figure 41B. Condition of Girder Joints over Bent No. 11 (West Bound).

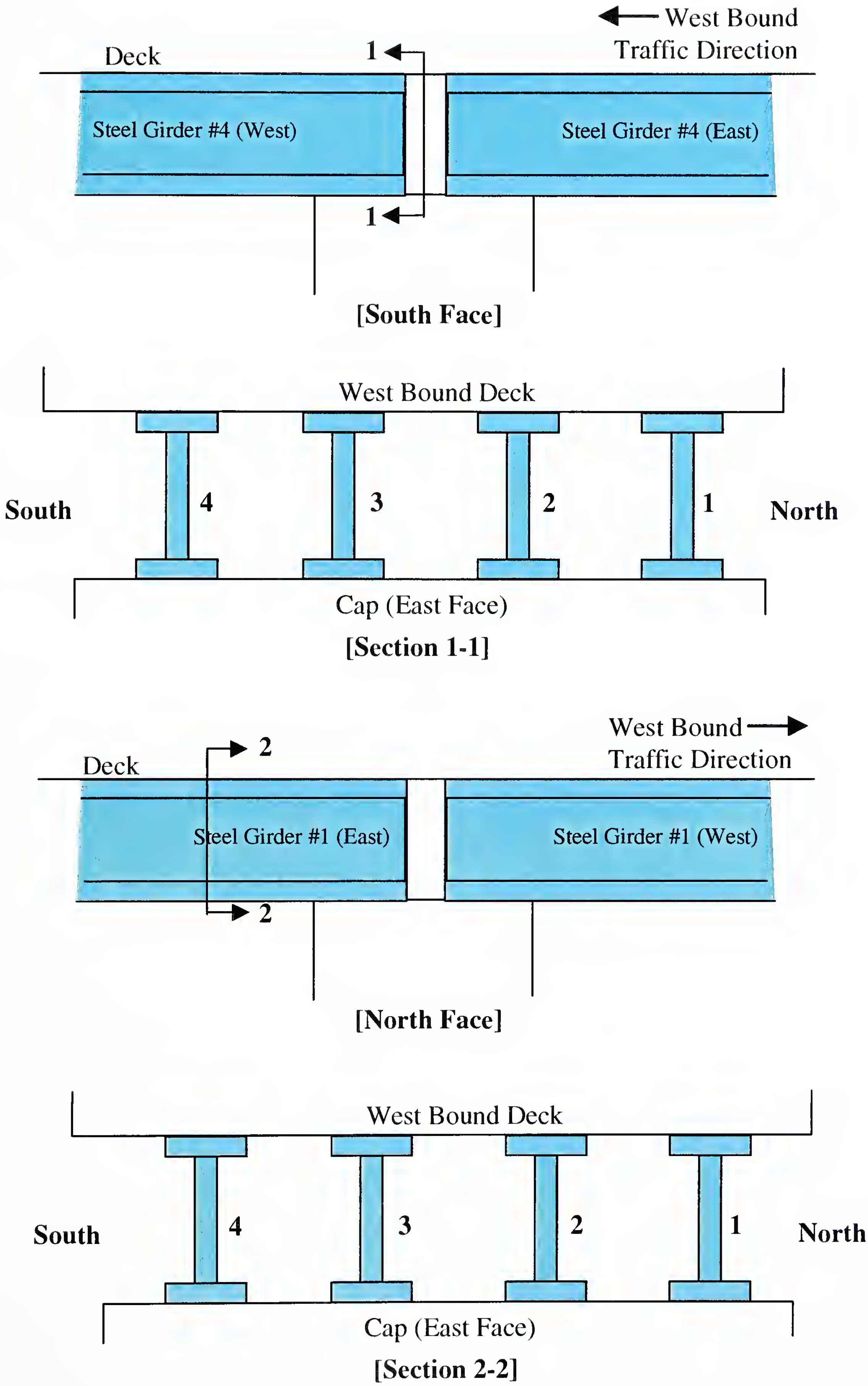


Figure 42B. Condition of Girder Joints over Bent No. 12 (West Bound).

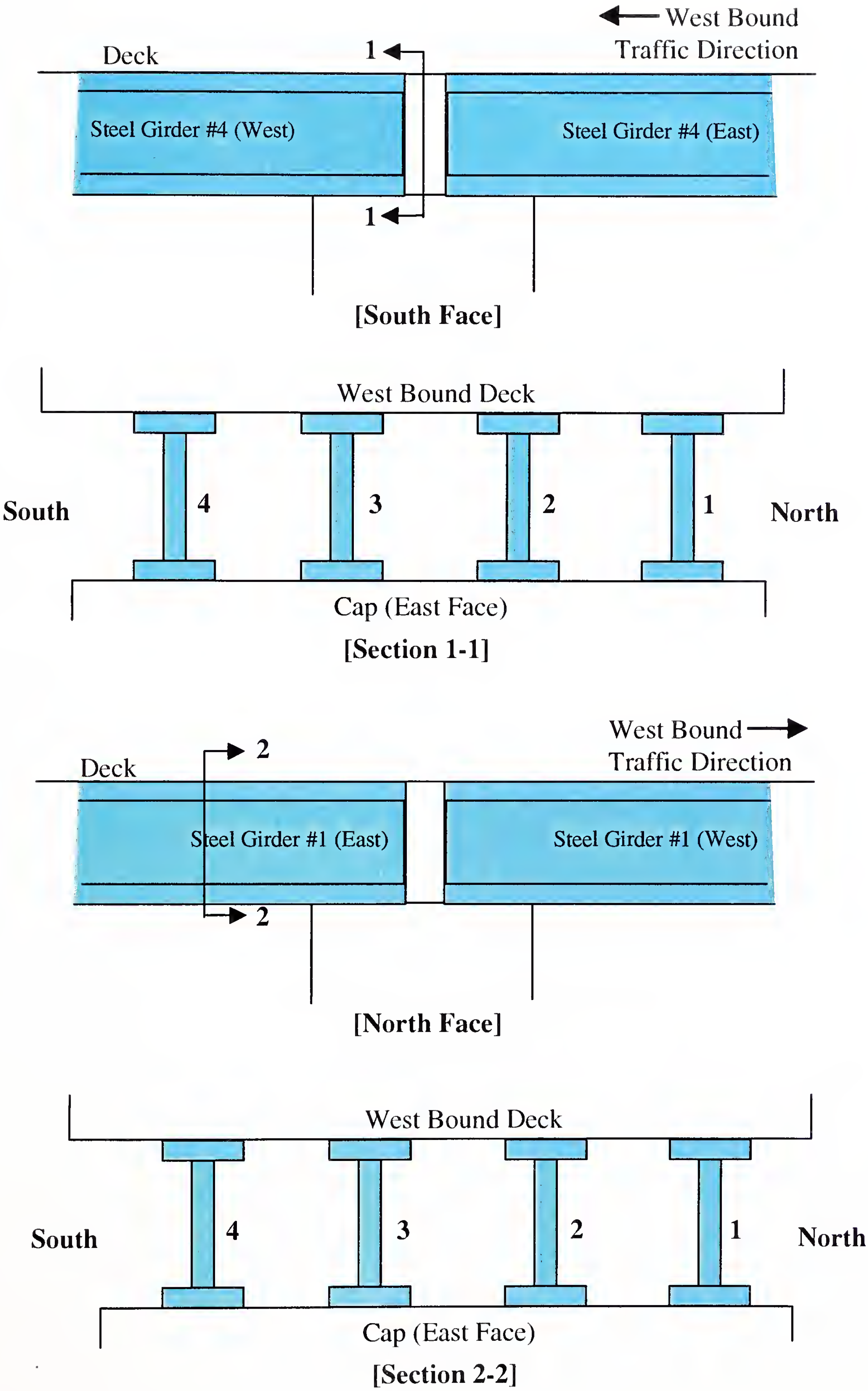


Figure 43B. Condition of Girder Joints over Bent No. 13 (West Bound).

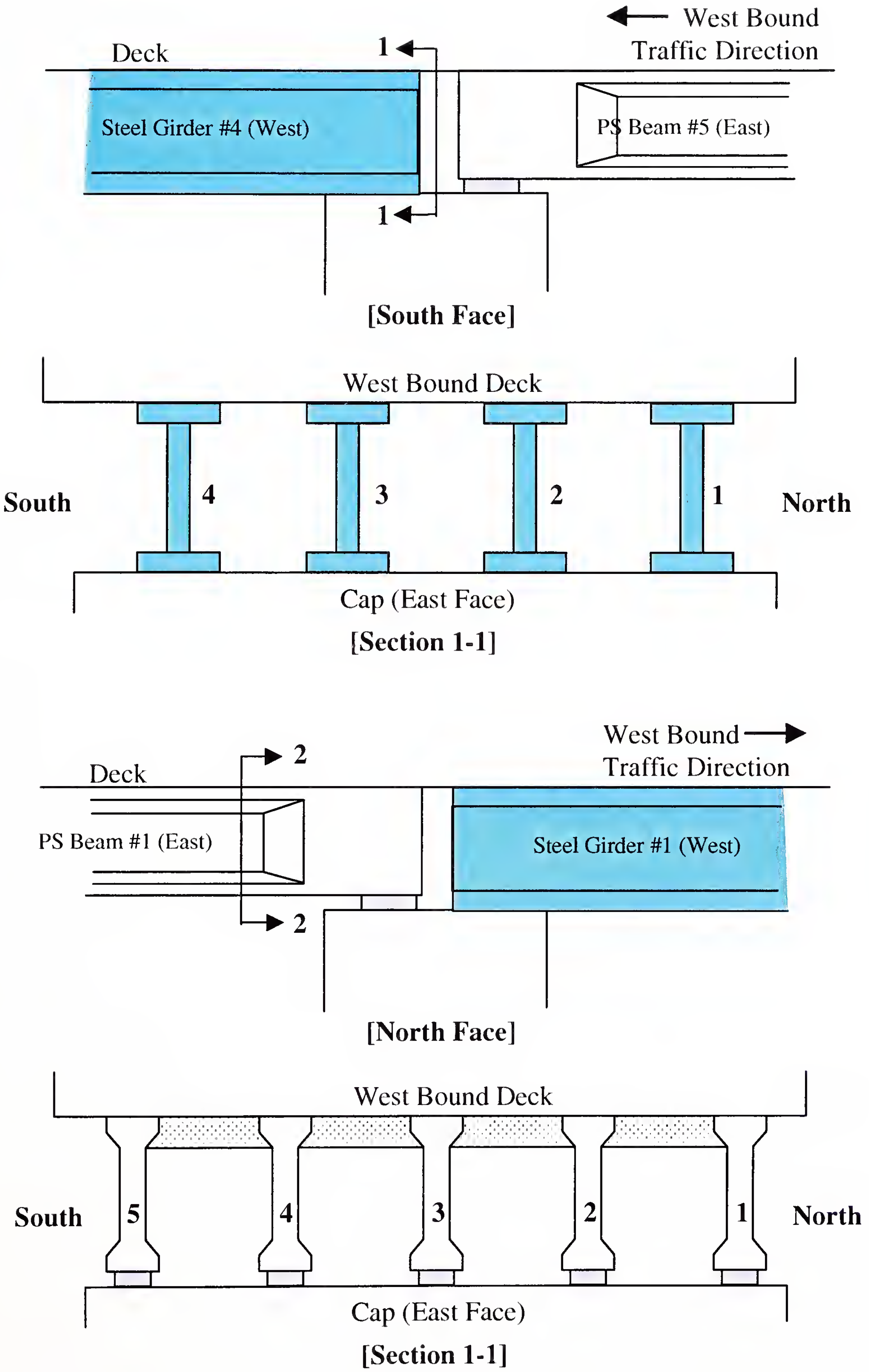


Figure 44B. Condition of Beam Joints over Bent No. 14 (West Bound).

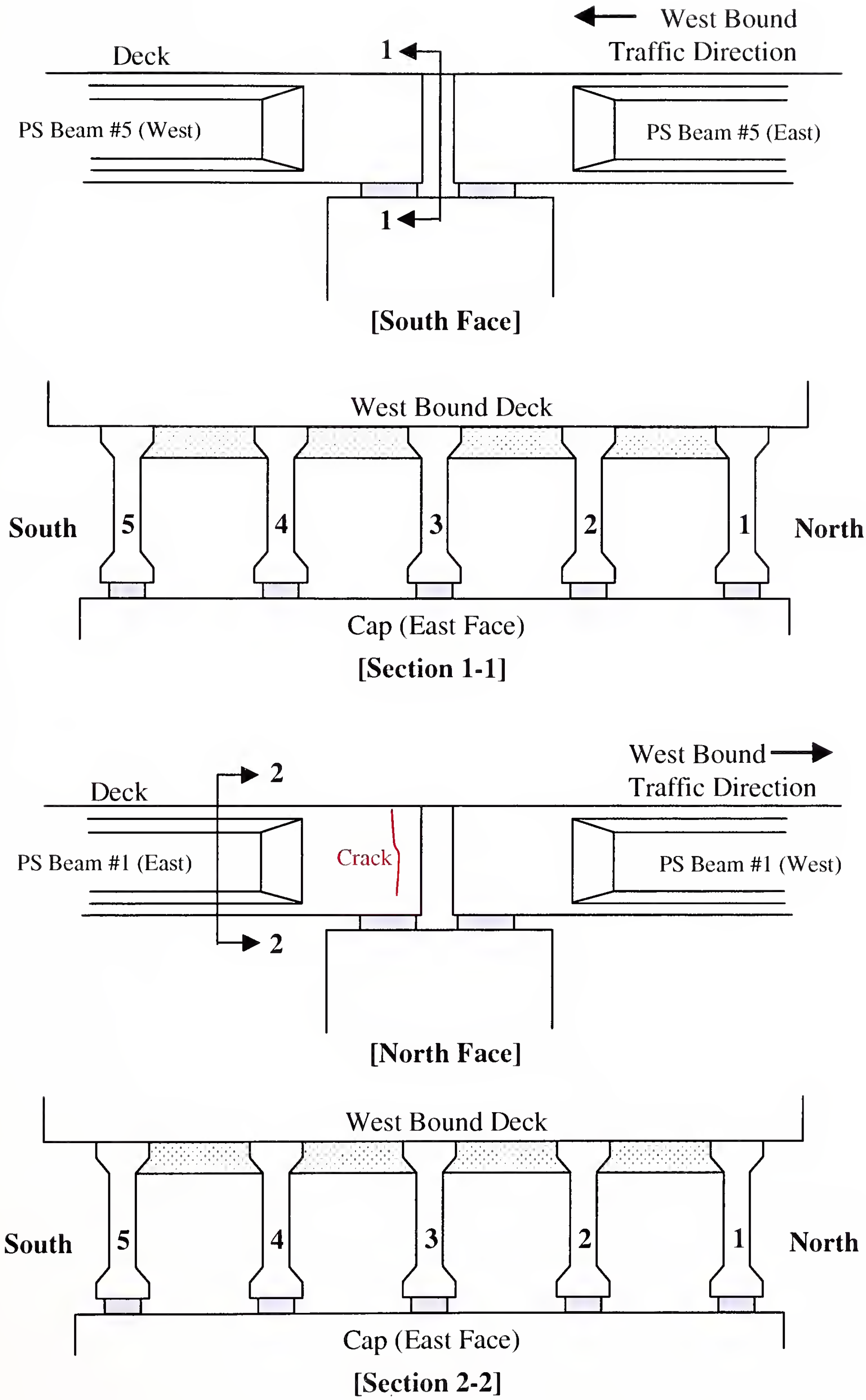


Figure 45B. Condition of Beam Joints over Bent No. 15 (West Bound).

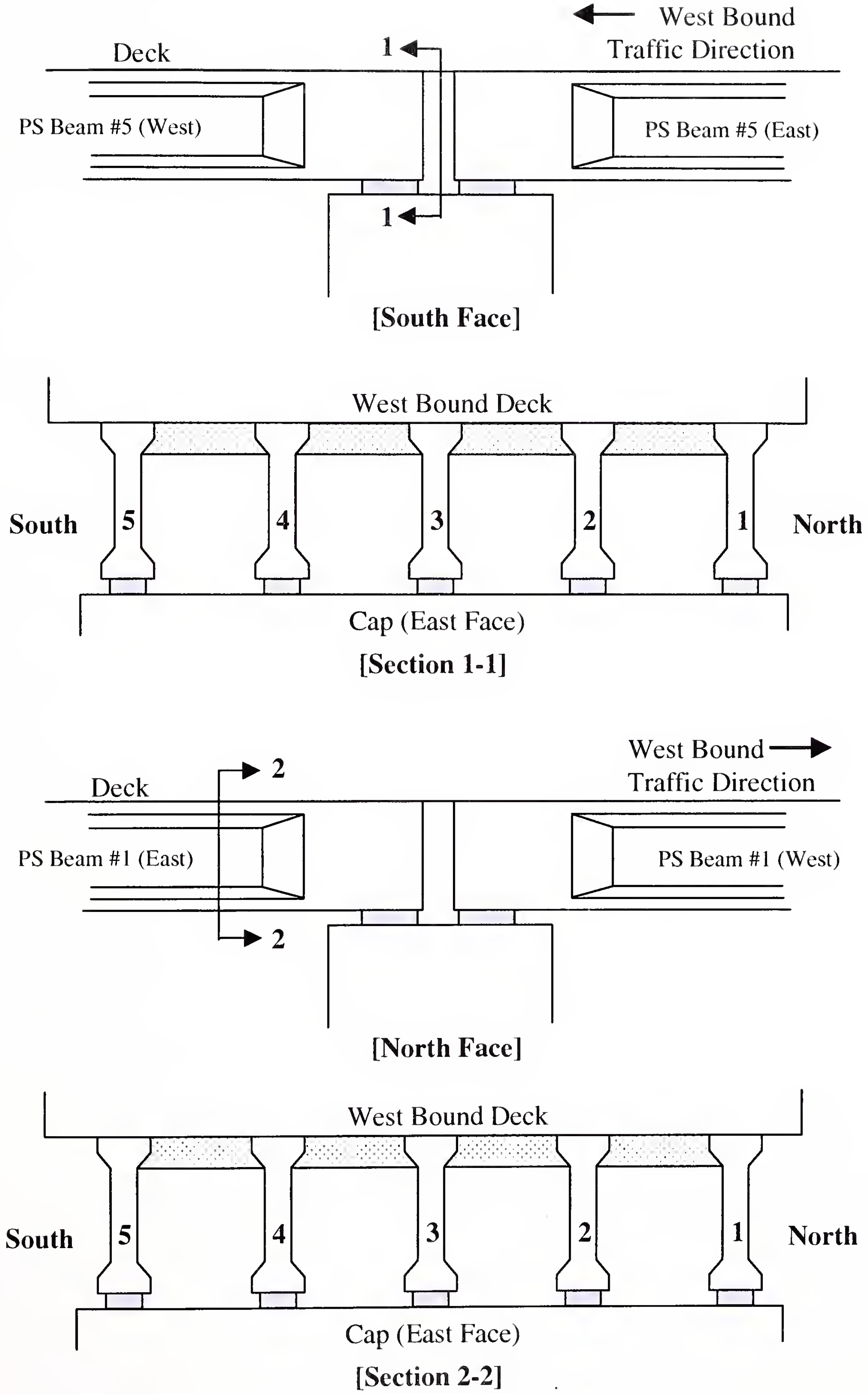


Figure 46B. Condition of Beam Joints over Bent No. 16 (West Bound).

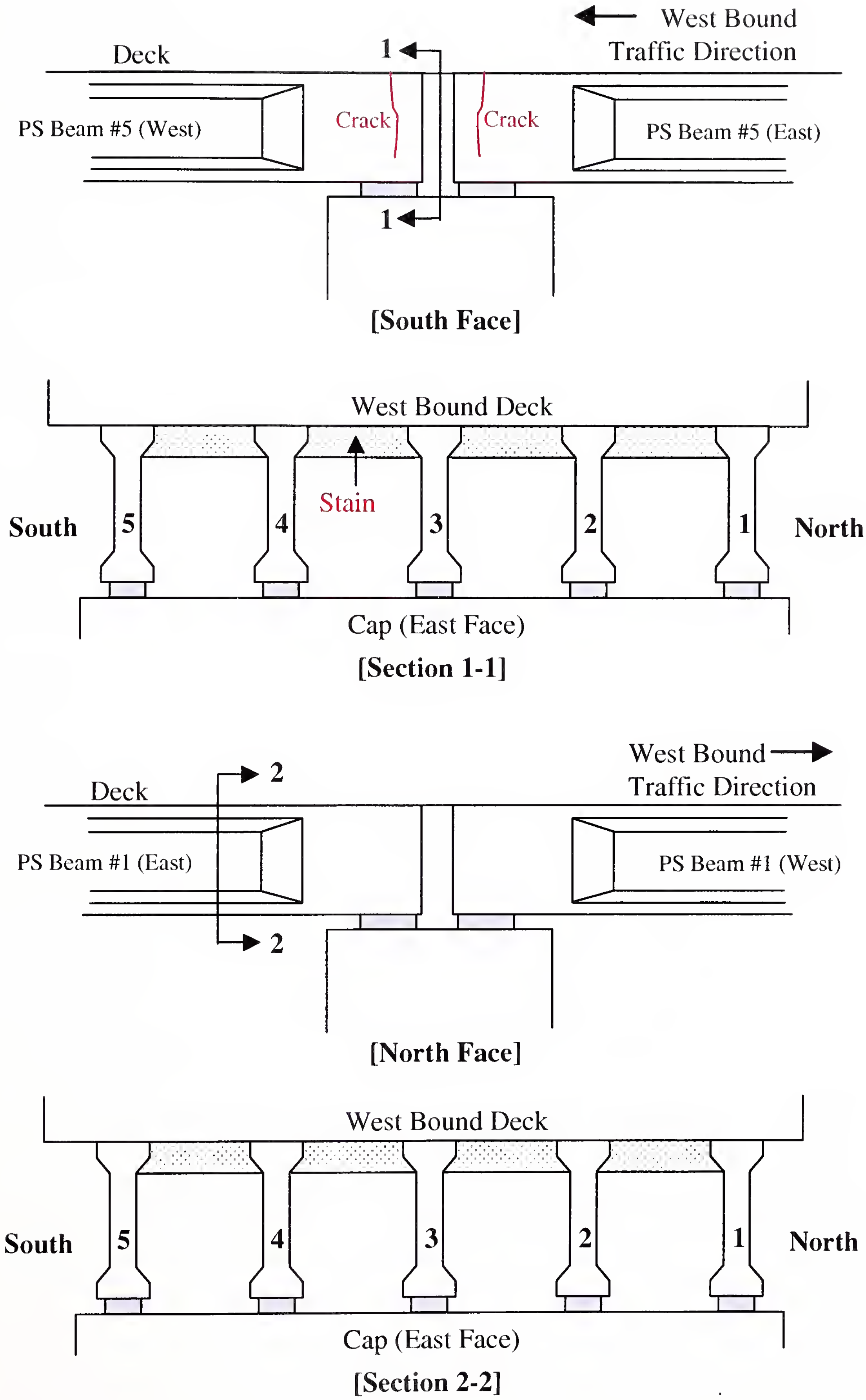


Figure 47B. Condition of Beam Joints over Bent No. 17 (West Bound).

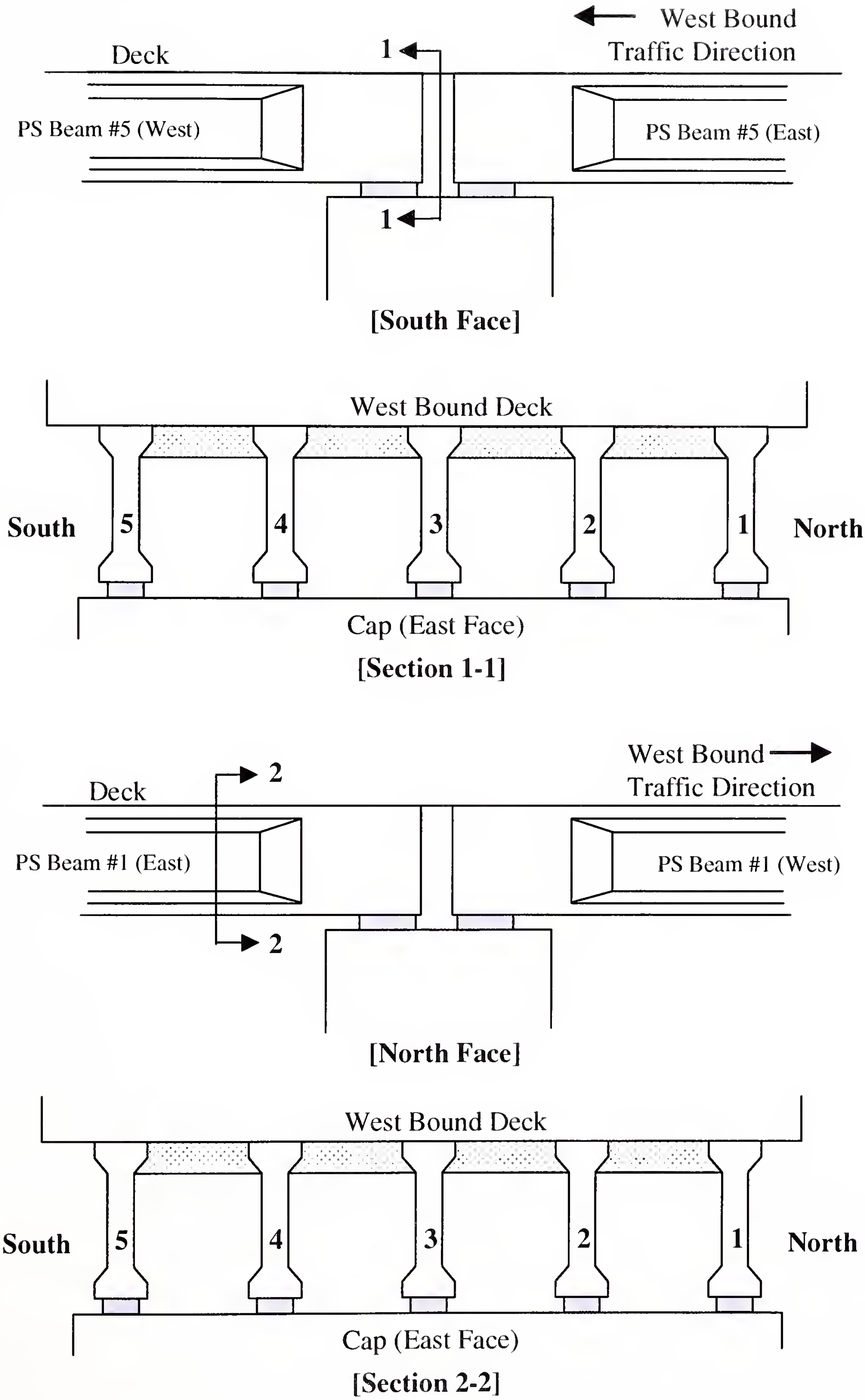


Figure 48B. Condition of Beam Joints over Bent No. 18 (West Bound).

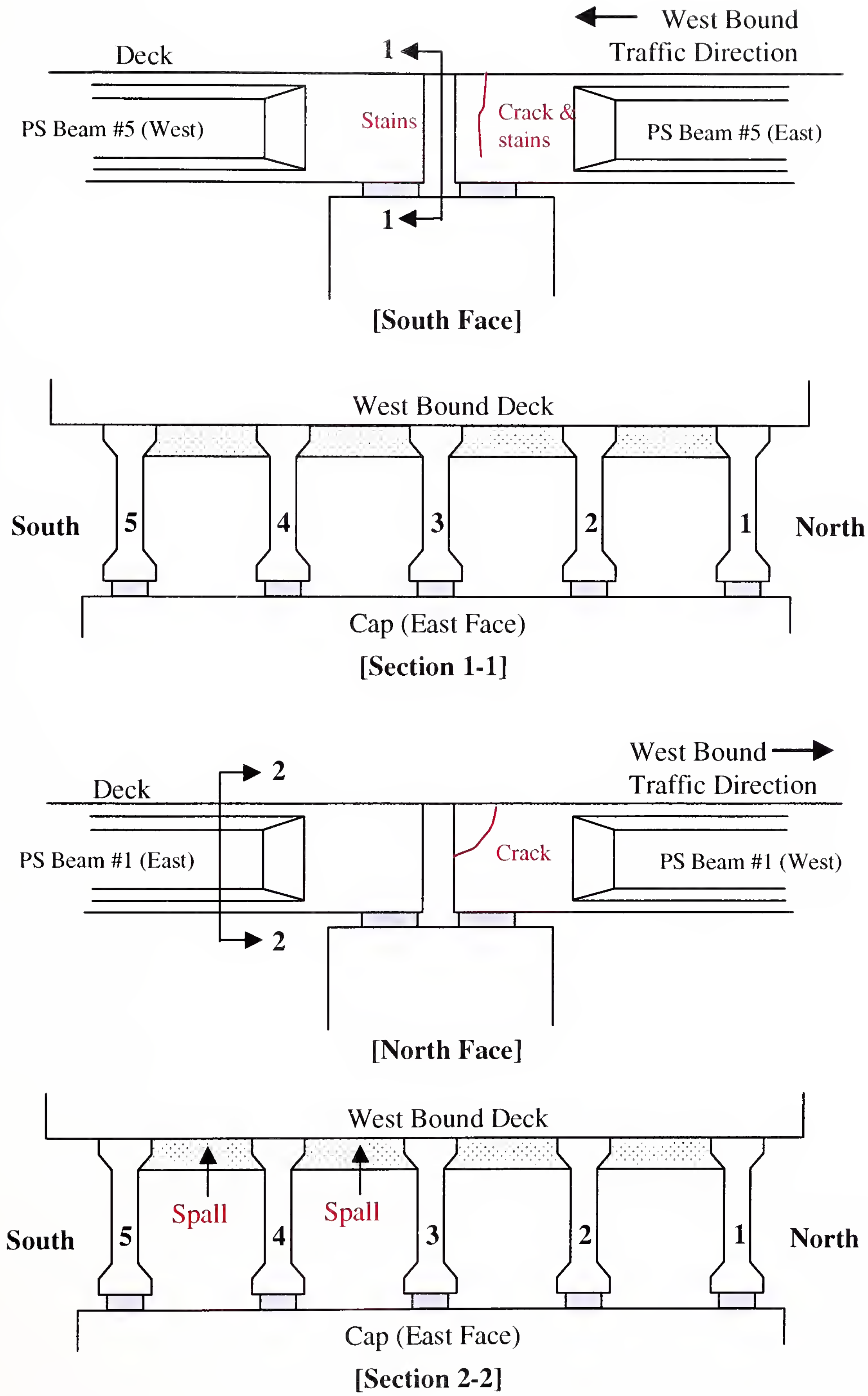


Figure 49B. Condition of Beam Joints over Bent No. 19 (West Bound).

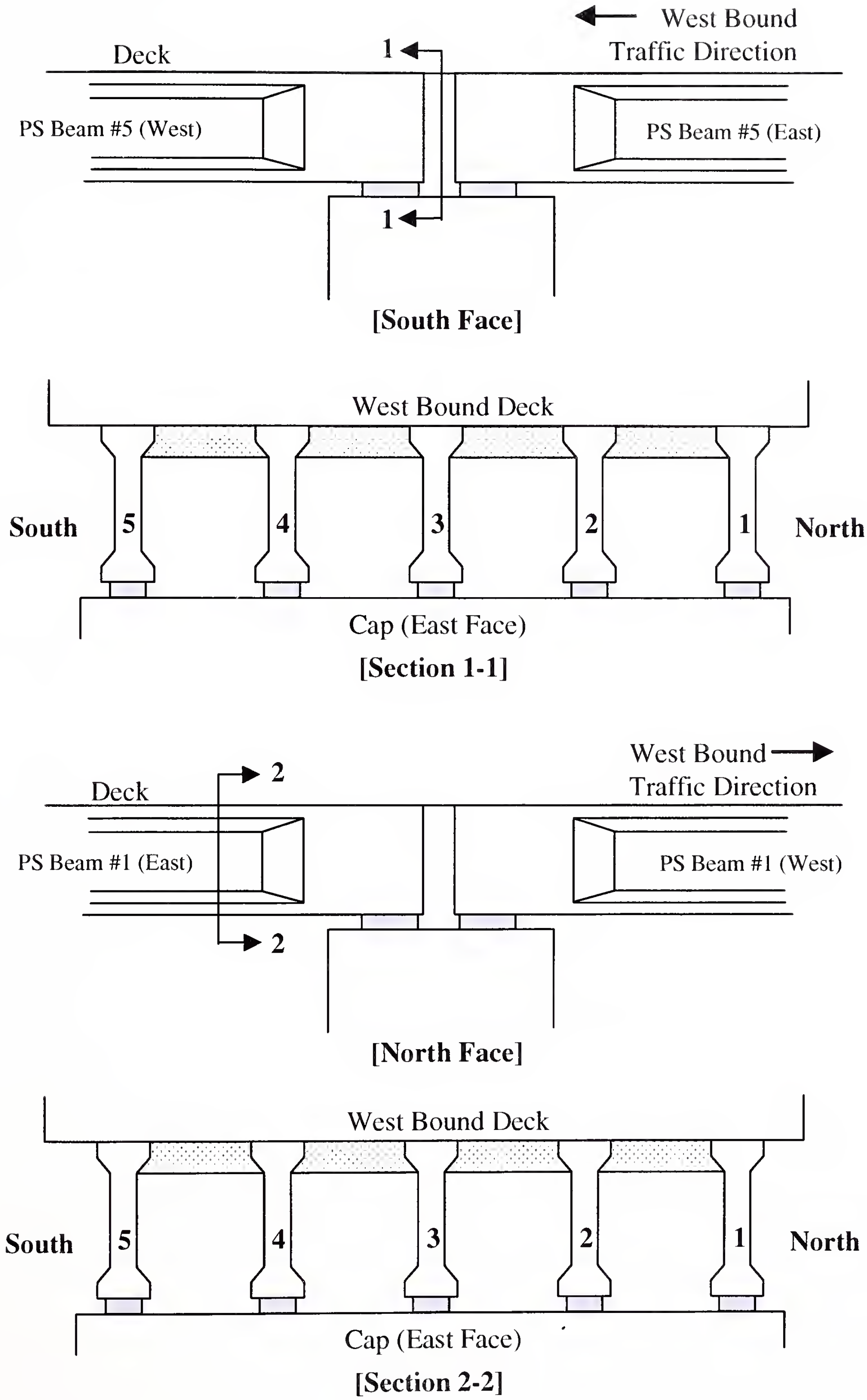
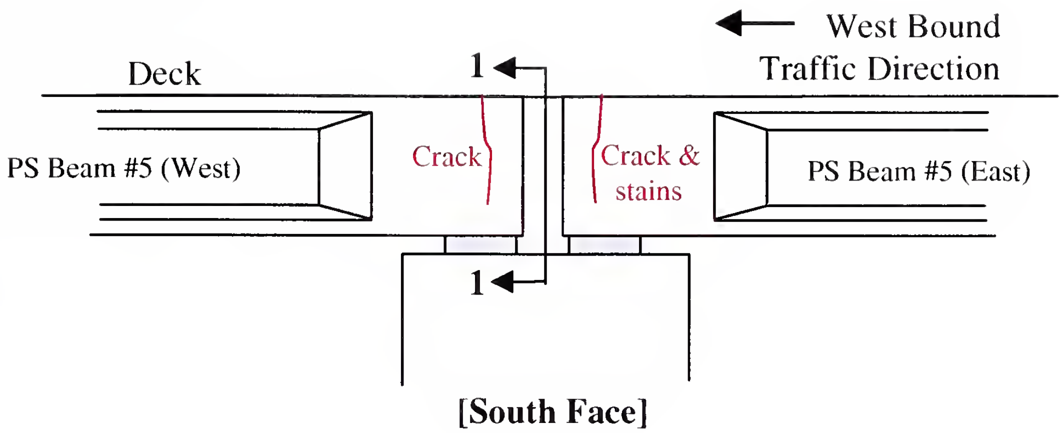
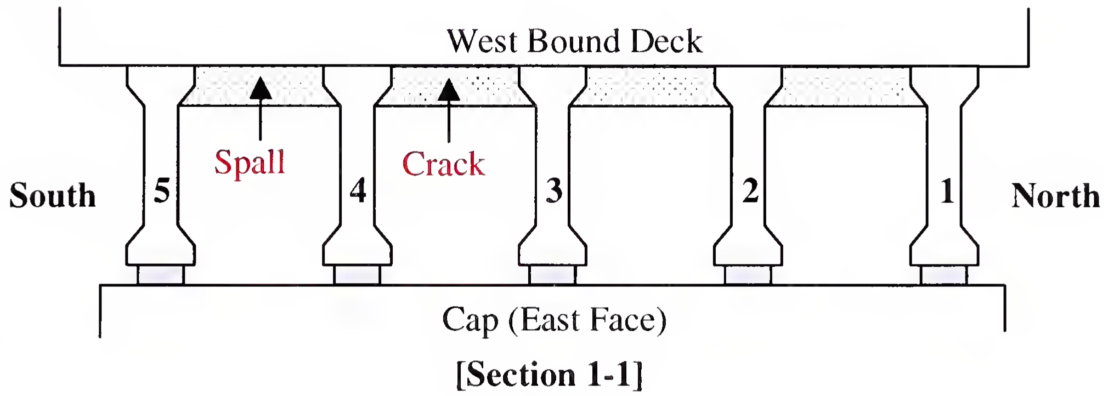
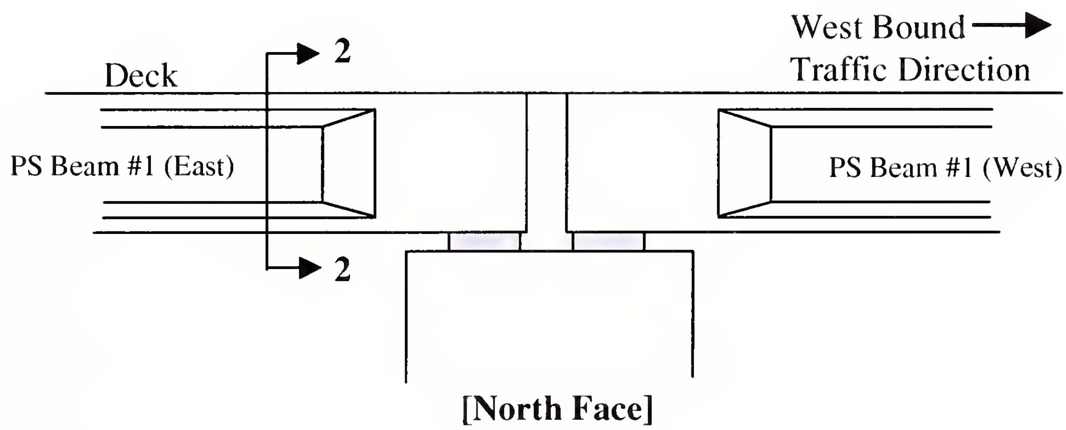


Figure 50B. Condition of Beam Joints over Bent No. 20 (West Bound).







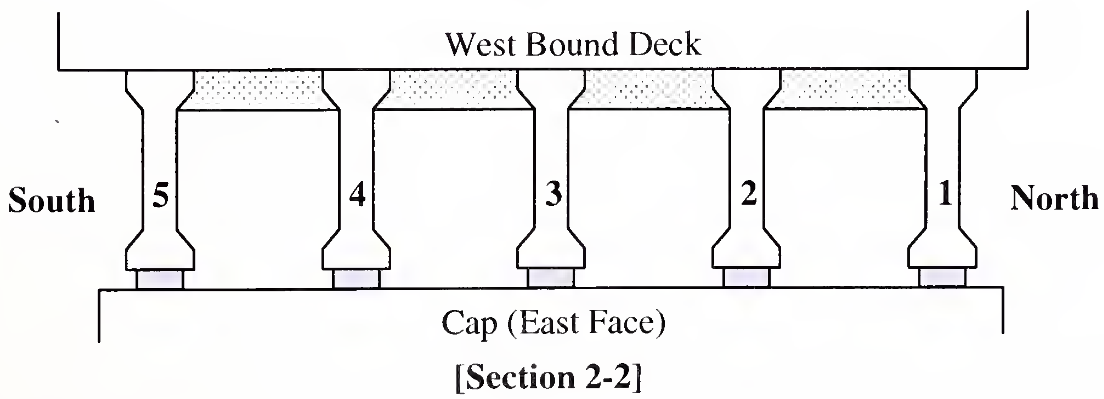


Figure 51B. Condition of Beam Joints over Bent No. 21 (West Bound).

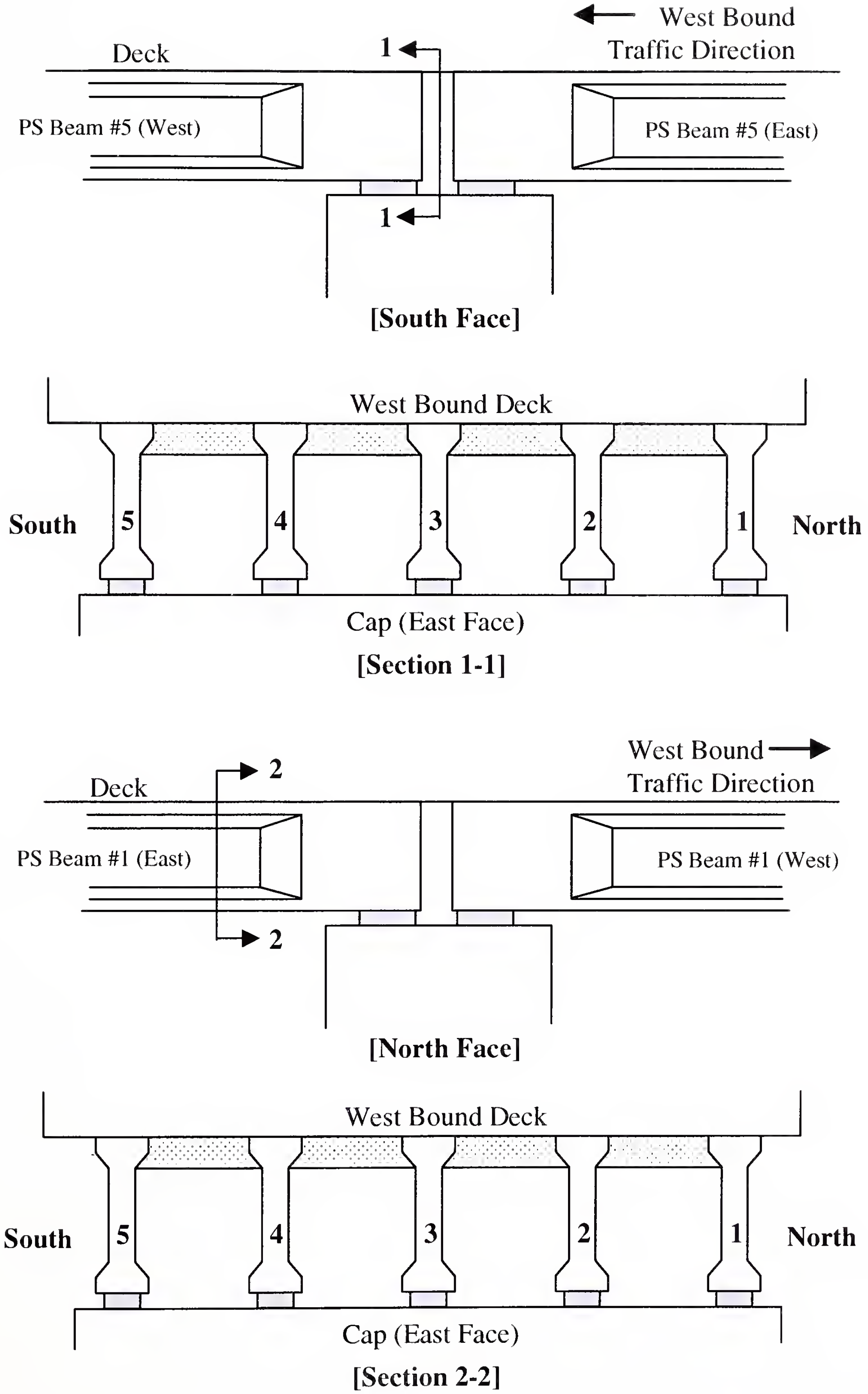


Figure 52B. Condition of Beam Joints over Bent No. 22 (West Bound).

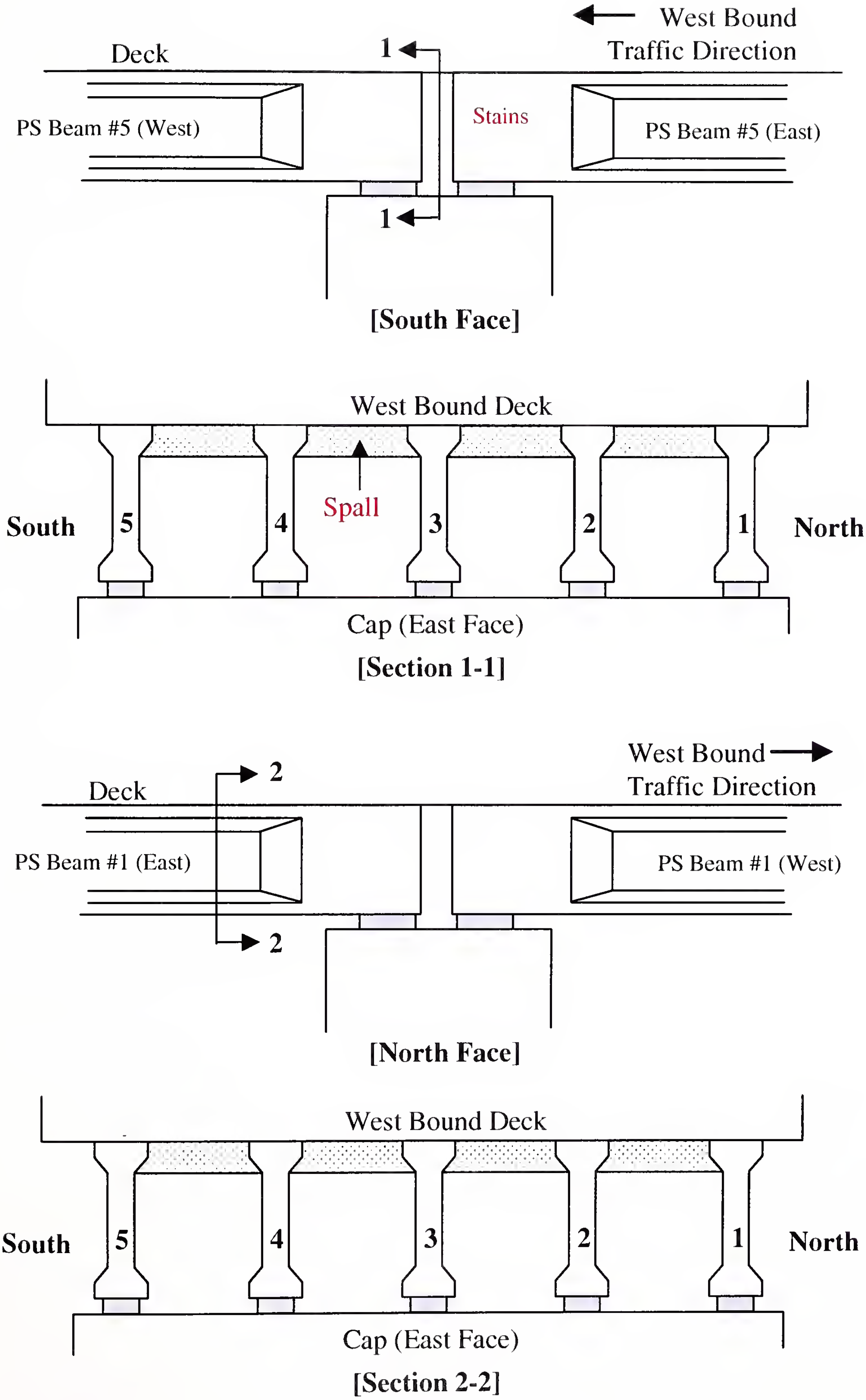
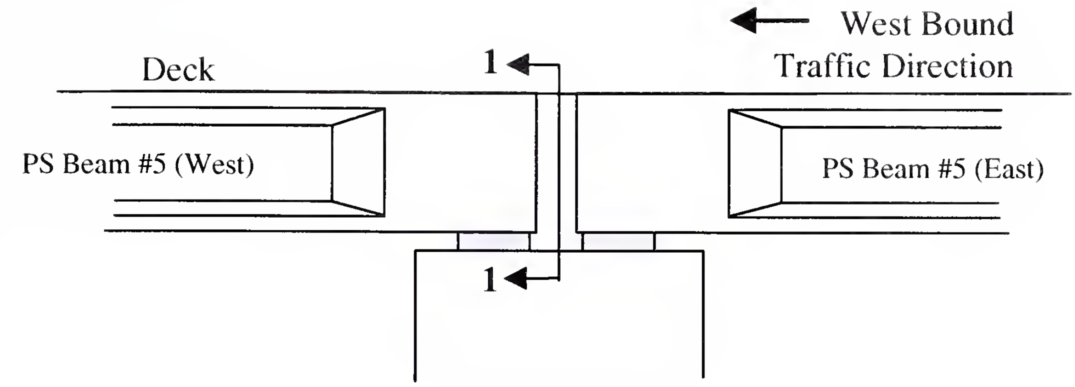
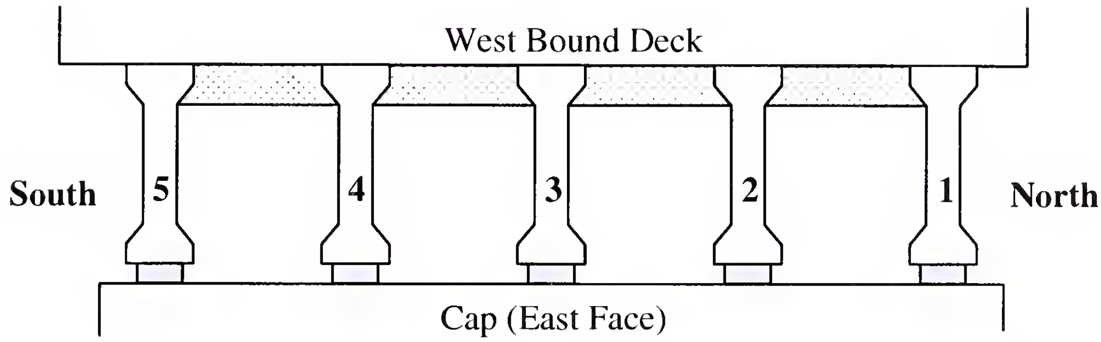


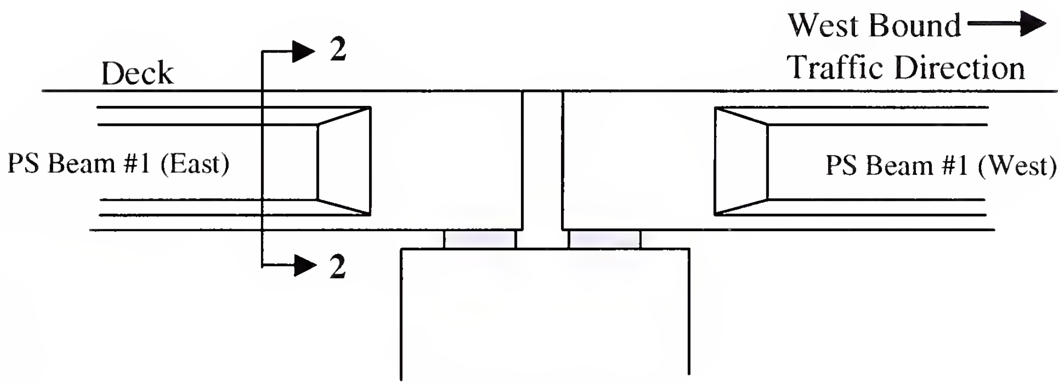
Figure 53B. Condition of Beam Joints over Bent No. 23 (West Bound).



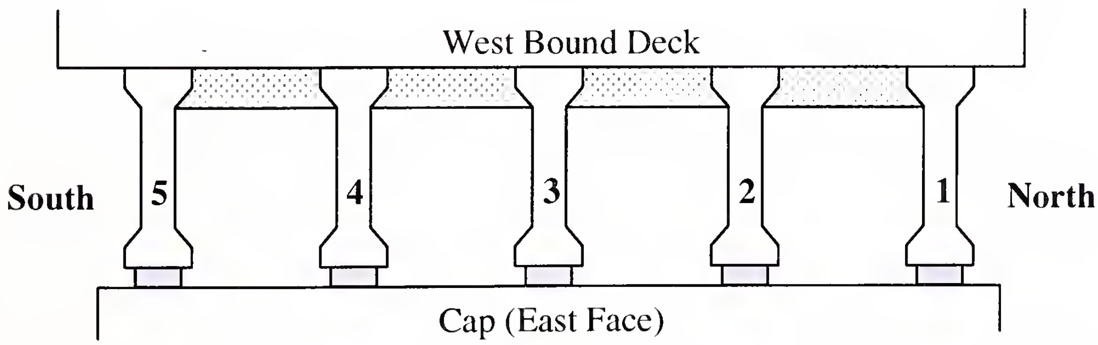
[South Face]



[Section 1-1]



[North Face]



[Section 2-2]

Figure 54B. Condition of Beam Joints over Bent No. 24 (West Bound).

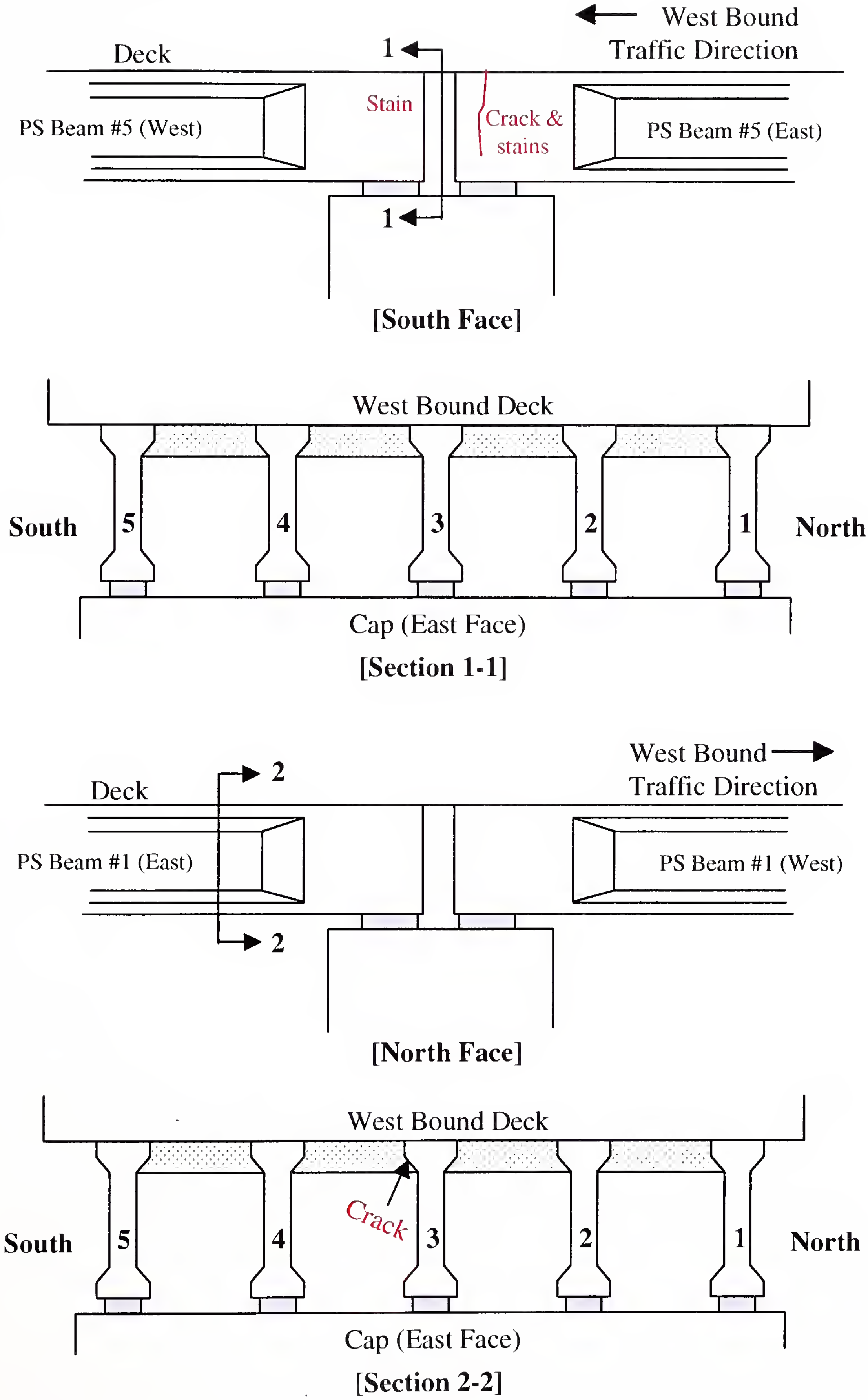


Figure 55B. Condition of Beam Joints over Bent No. 25 (West Bound).

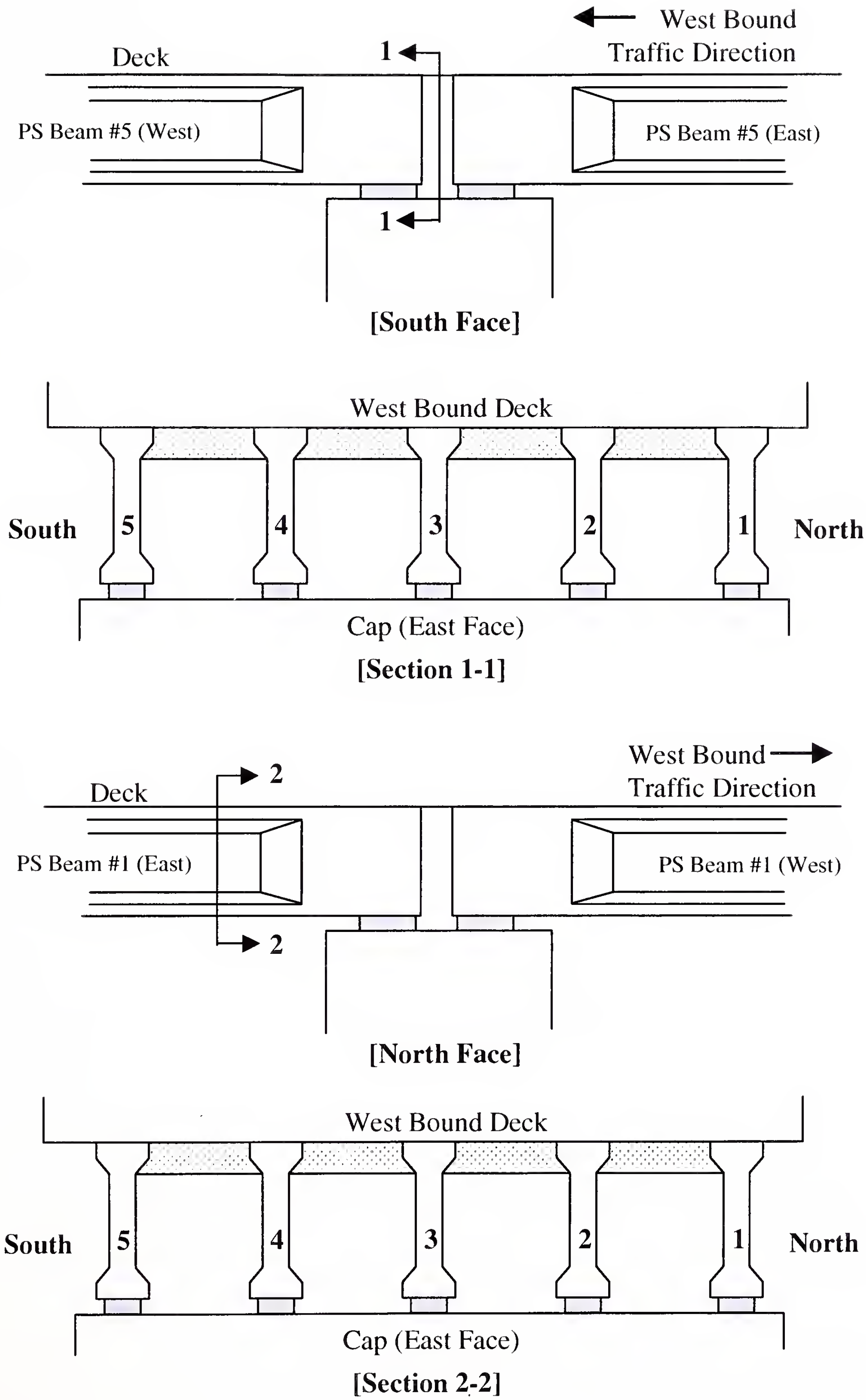
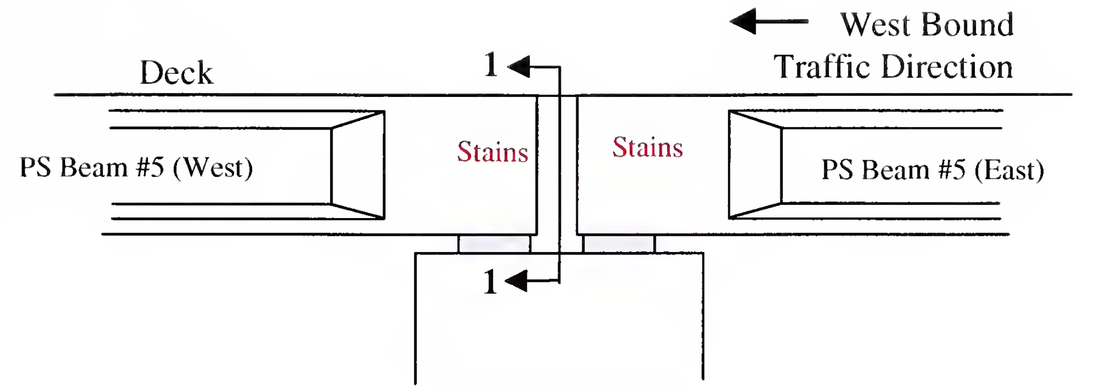
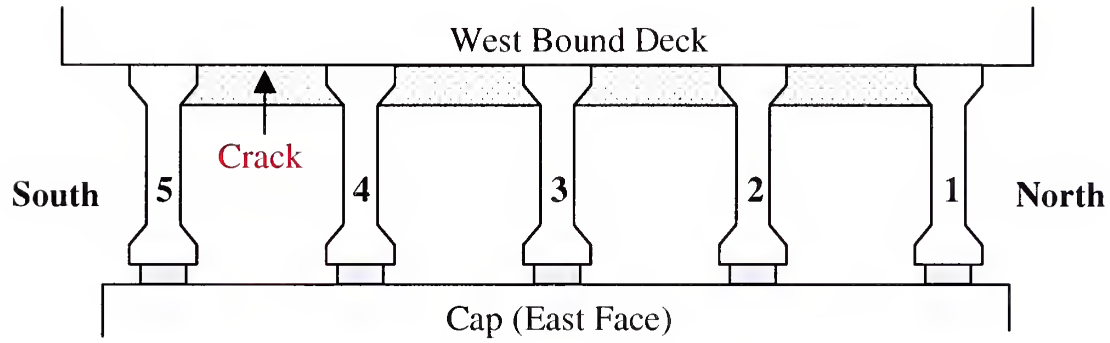


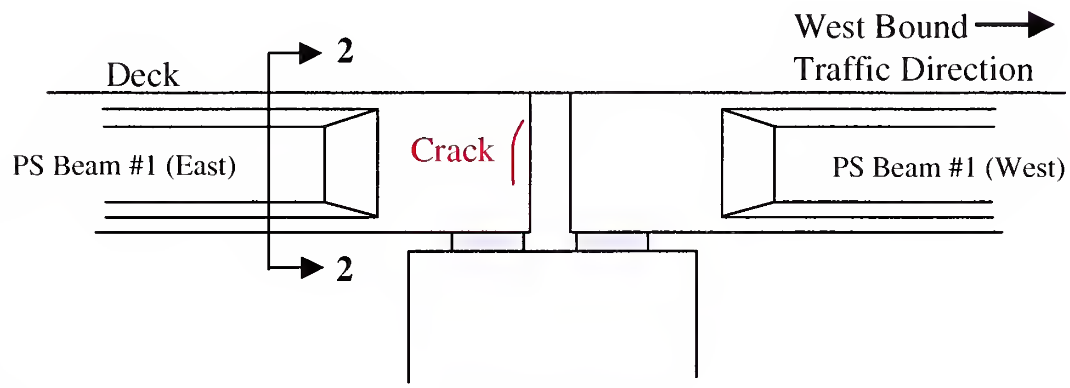
Figure 56B. Condition of Beam Joints over Bent No. 26 (West Bound).



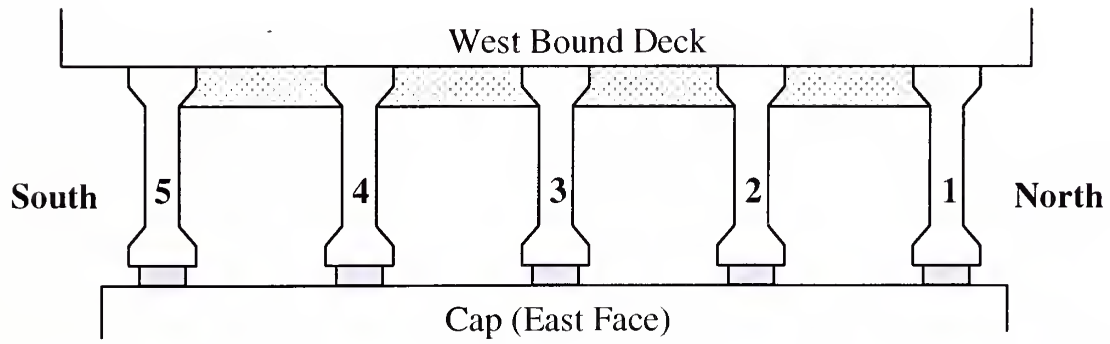
[South Face]



[Section 1-1]



[North Face]



[Section 2-2]

Figure 57B. Condition of Beam Joints over Bent No. 27 (West Bound).

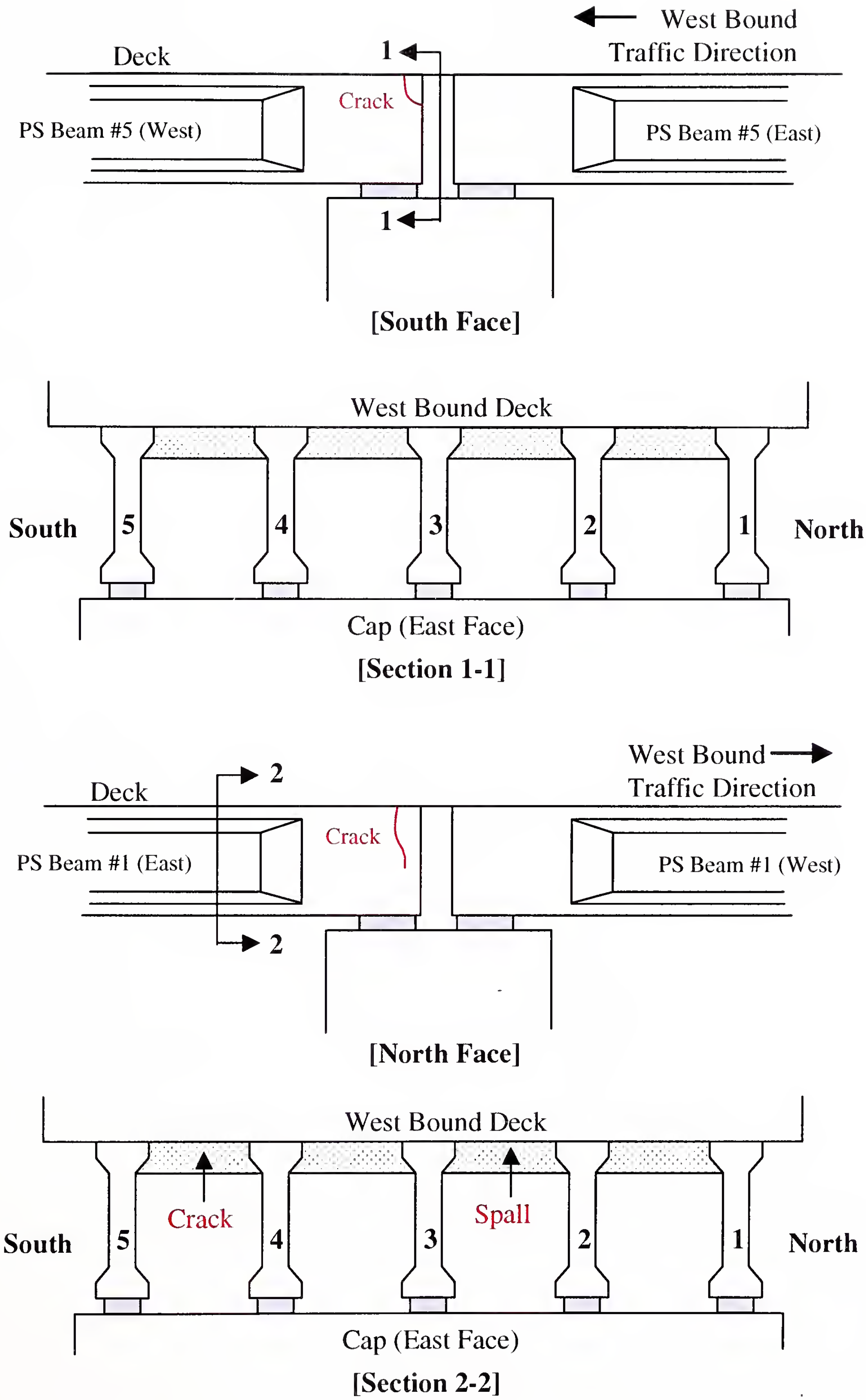


Figure 58B. Condition of Beam Joints over Bent No. 28 (West Bound).

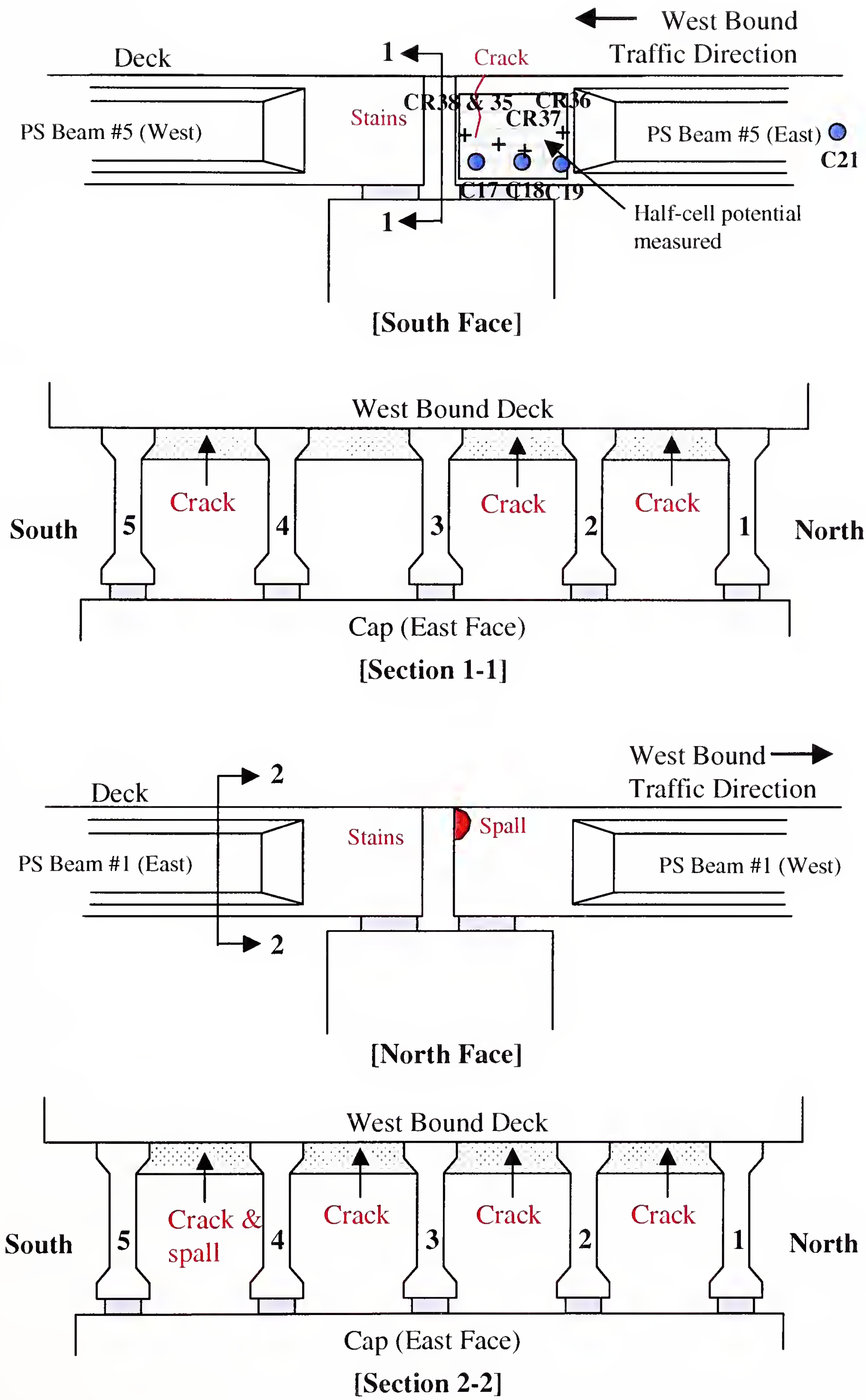


Figure 59B. Condition of Beam Joints over Bent No. 29 (West Bound).

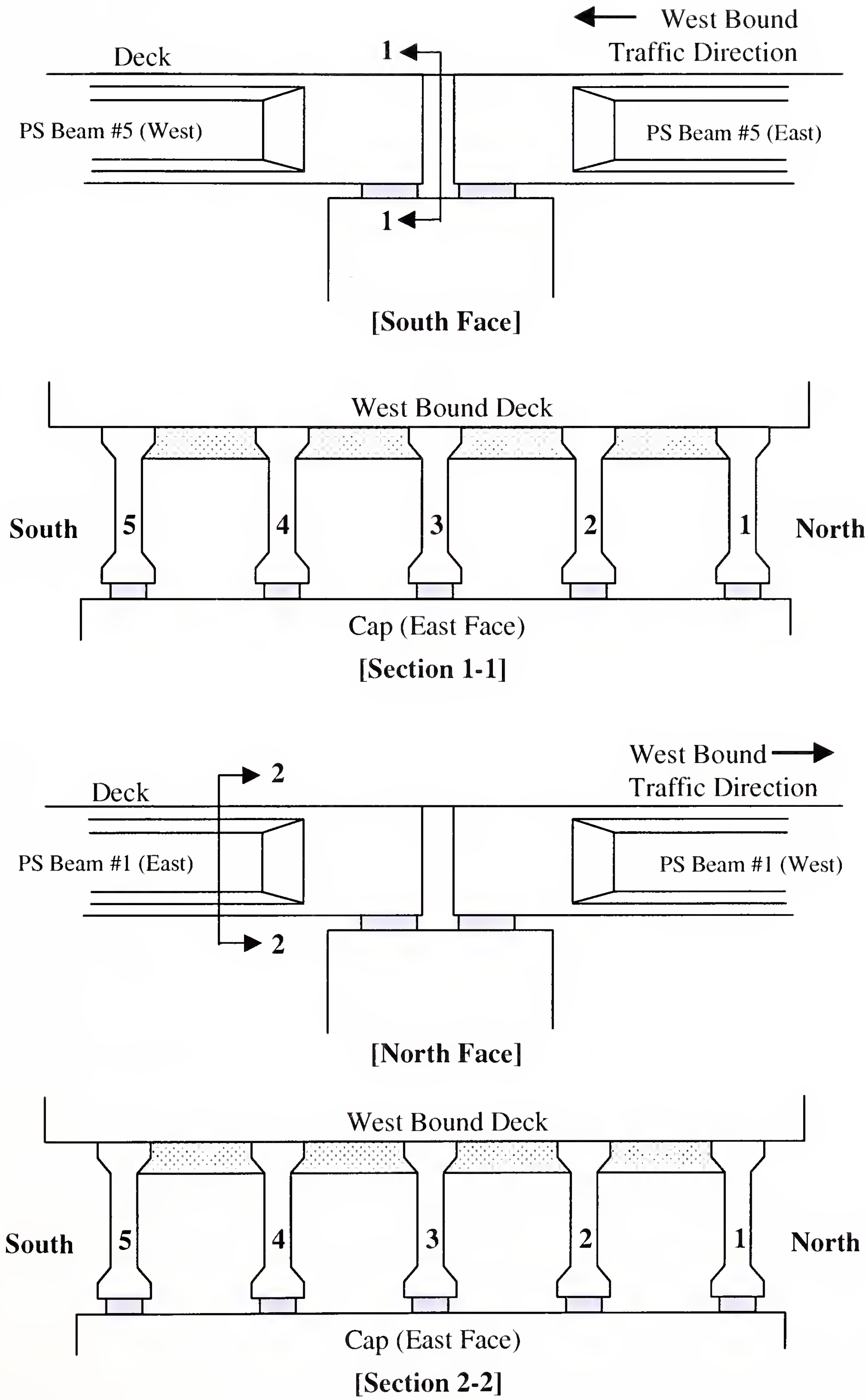


Figure 60B. Condition of Beam Joints over Bent No. 30 (West Bound).

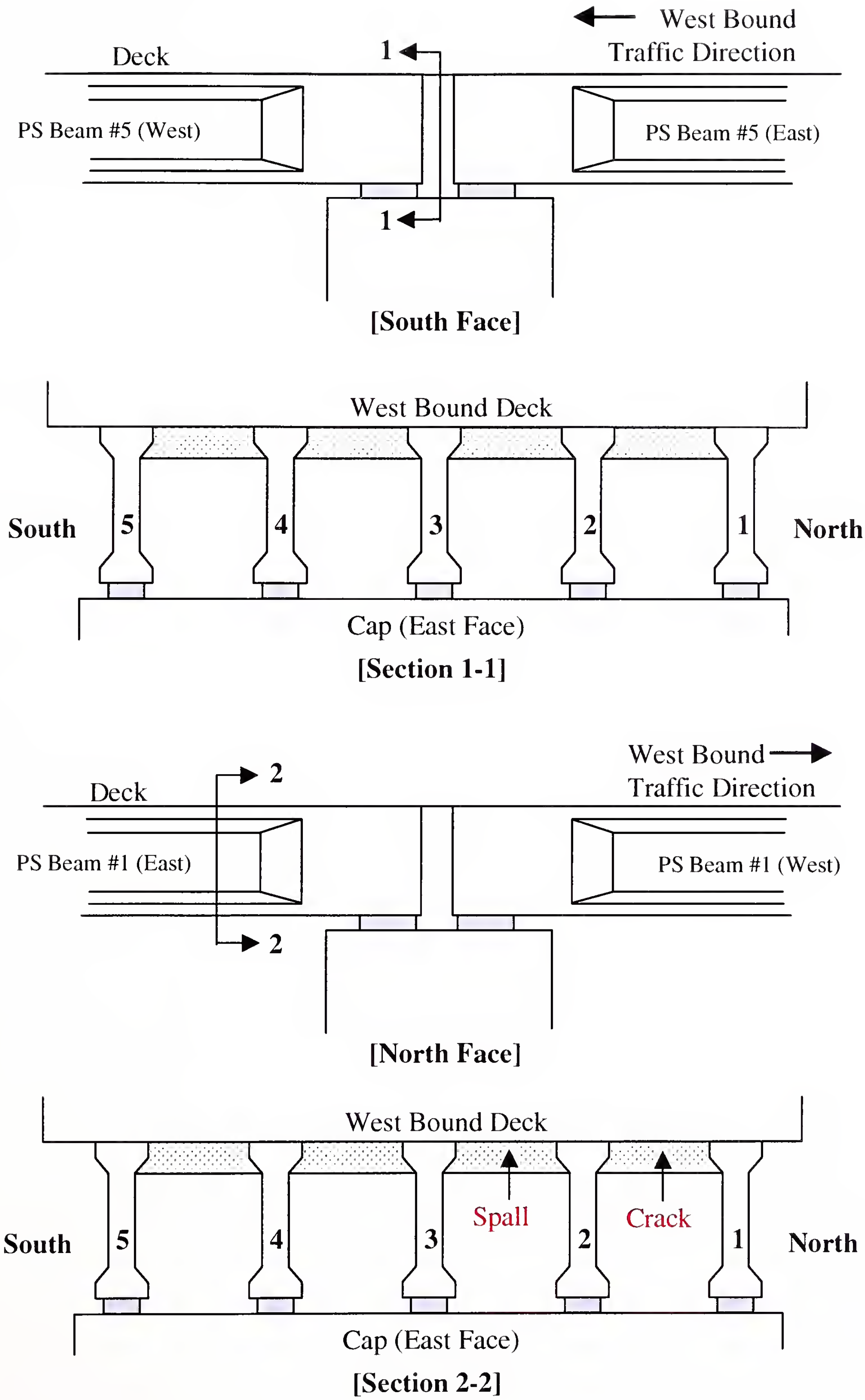


Figure 61B. Condition of Beam Joints over Bent No. 31 (West Bound).

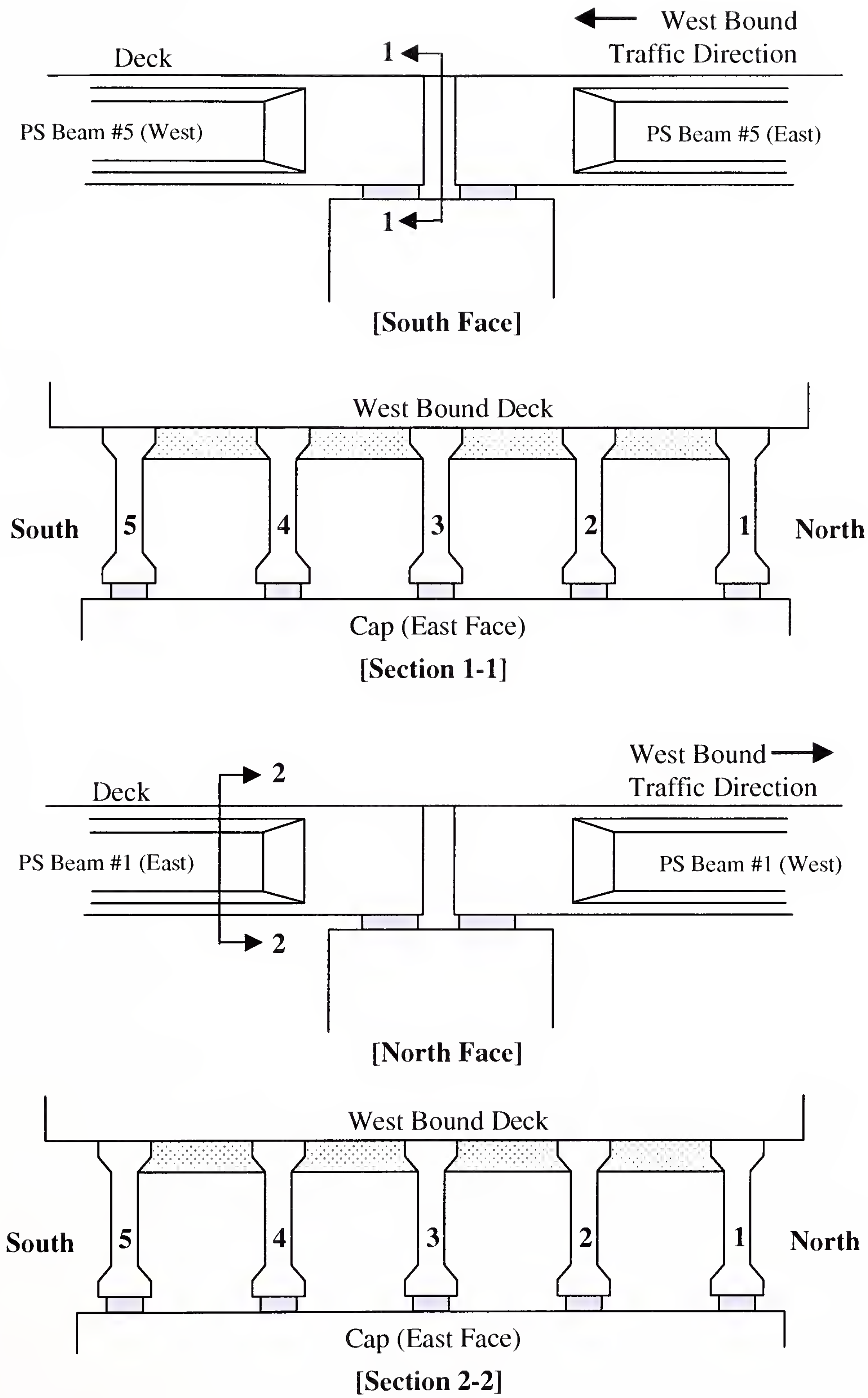


Figure 62B. Condition of Beam Joints over Bent No. 32 (West Bound).

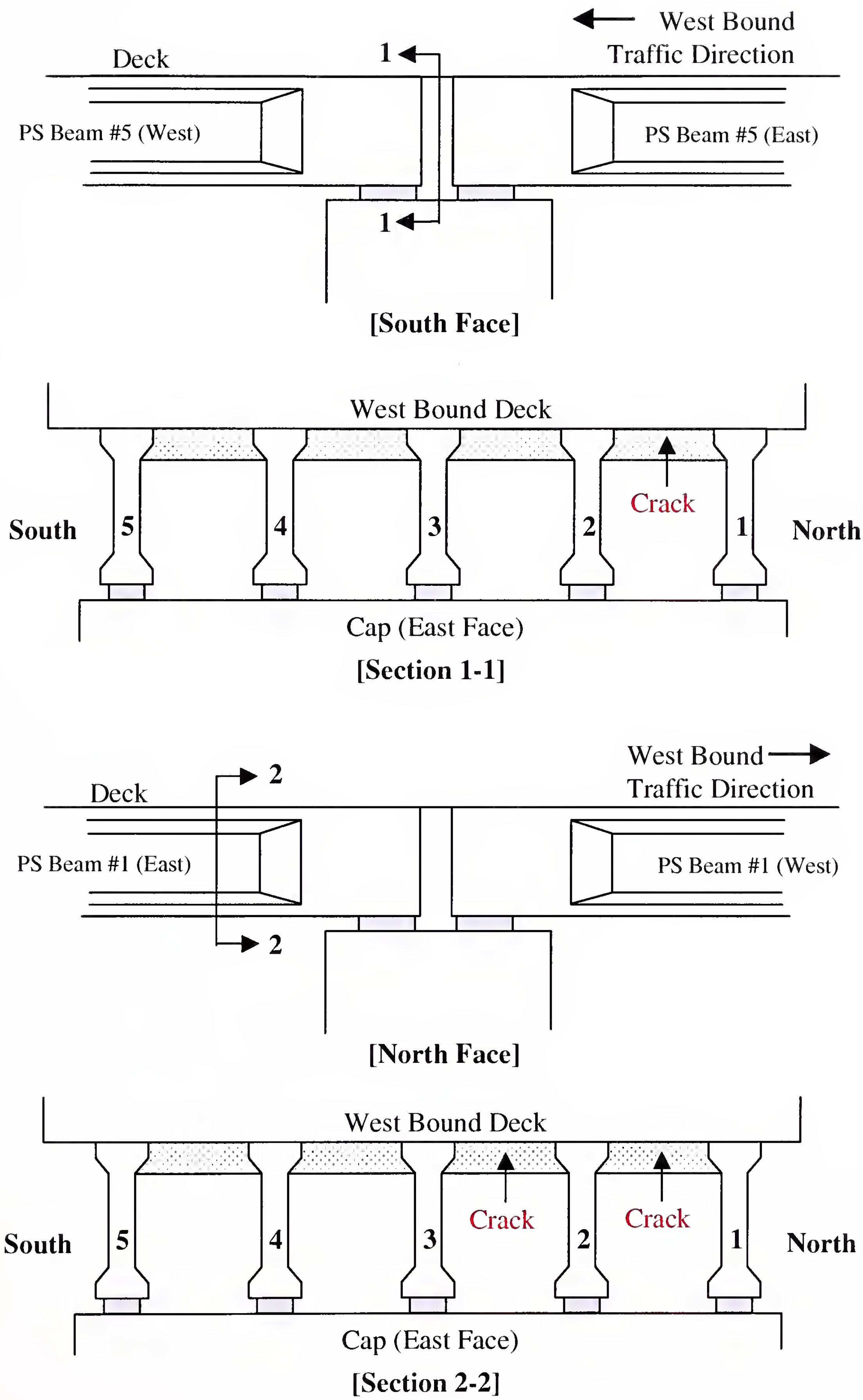


Figure 63B. Condition of Beam Joints over Bent No. 33 (West Bound).

APPENDIX C

Petrographic Examination Report

PETROGRAPHIC STUDIES OF CONCRETE

FOR

MONTANA DEPARTMENT OF TRANSPORTATION

WJE No. 2000.2547

November 29, 2000

WISS, JANNEY, ELSTNER ASSOCIATES, INC.
9425 Olde Eight Rd., Unit 2
Northfield Center, OH 44067

(330) 468-3929

November 29, 2000

PETROGRAPHIC AND STUDIES OF CONCRETE

FOR

MONTANA DEPARTMENT OF TRANSPORTATION

WJE No. 2000.2547

****

INTRODUCTION

At the request of Mr. Paul Krauss of our Northbrook, Illinois office, on behalf of the Montana Department of Transportation, petrographic studies of concrete cores from the Montana Avenue Overpass in Billings, Montana were conducted. The cores represent concrete that is approximately 39 years old. The studies were initiated to characterize the concrete and aid in determining the cause of observed cracking.

STUDIES

Samples

Five cores were received by the Cleveland office for the current studies. The cores, identified as 4, 5, 9 and 15, had a diameter of 3.7 inches. Of these four cores, all except for Core 5 had a total length of approximately 5.5 inches. Core 5 had a total length of approximately 2.5 to 3 inches. Each of the cores had a fractured bottom surface. The top surfaces of Cores 4, 5 and 9 were grooved and the top surfaces of Cores 15 and 28 were formed. Steel reinforcement was detected in Cores 9 and 15 at depths of approximately 2.5 inches. Both Cores 4 and 5 had impressions of steel reinforcement on the bottom fractured surfaces. No metal reinforcement was detected in Core 28. Cores 15 and 28 were designated for full petrographic studies and fractures on Cores 4, 5, and 8 were examined.

Cores 15 and 28 were cut in half (longitudinally) using a continuous-rim diamond saw blade. The resulting plane surfaces were oriented parallel to the axes of the core. One cut surface of each core was lapped using progressively finer silicon carbide abrasives. The lapped surfaces and the remainders of the cores were then examined using methods outlined in ASTM C457 "Standard Test Method for

Microscopical Determination of Parameters of the Air-void System of Hardened Concrete" and ASTM C856 "Standard Practice for Petrographic Examination of Hardened Concrete."

Petrographic Studies

Fractures were detected on the top surfaces of all the cores. The fractures at the tops of Cores 4, 5 and 9 were approximately 0.075 inch wide at the surface where they had likely experienced some erosion. These fractures decrease in width to less than 0.010 inch or less at depths of 0.05 inch below the existing surface. The fractures in Core 5 and 9 extended the full-depth of the cores. Dirt and debris were detected all along those fractures (Photo 1). The fracture in Core 4 only extended 0.5 to 1 inch into the core, but dirt and debris were also detected along this fracture.

The fractures detected on the formed surfaces of Cores 15 and 28 were not eroded like those in the cores described above and averaged 0.004 inches wide. These fractures extended to depths of approximately 1 inch in Core 15 and to less than 0.25 inch in Core 28. None of the fractures detected in any of the five submitted cores passed through aggregate particles.

The coarse aggregate contained within Cores 15 and 28 was composed of a rounded gravel consisting of igneous rocks such as granite and basalt. The fine aggregate was natural siliceous sand. There was no evidence of deleterious reaction between the aggregate and the cementitious matrix.

The cementitious matrix was gray, relatively hard, had a sub-vitreous luster, and contained numerous unhydrated cement particles. Slight mottling of the cement paste was present, indicating that there was some minor variability in the water to cement ratio, but these characteristics suggest that the water to cement ratio was moderate to moderately low. Clear rims surrounded some unhydrated cement particles, evidence of restricted hydration. Phenolphthalein indicator solution was applied to freshly fractured surfaces (of all submitted cores) induced in the laboratory in order to determine the depth of complete cement paste carbonation. Core 4 was carbonated to a depth of approximately 1-inch. Cores 5 and 15 were carbonated from 0 to 0.25 inch. The deepest parts of the carbonated zone occurred around pre-existing fractures. Core 9 was not carbonated. Core 28 was carbonated to a depth of 0.2 inch.

The concrete represented by Core 15 was air-entrained and most of the air voids were very small, with an estimated volume of 4 to 7% of the concrete. Cores 4, 5 and 9 appeared to have similar air contents. Very tiny tufts of needle-shaped crystals were present as secondary deposits within some of the air voids of Core 15 (Photos 2). These secondary deposits are likely ettringite and suggest that water is moving through the concrete. The concrete represented by Core 28 was not air-entrained but did contain some large, irregularly shaped voids that are characteristic of entrapped air.

CONCLUSIONS

The observed cracks are very likely due to shrinkage of the cement paste. The deeper carbonated paste around the pre-existing fractures suggest that the fractures opened up over time. Dirt and debris were detected all along the fractures. The presence of soil along the fractures and the secondary deposits of ettringite in some of the air voids suggest that water is able to move easily throughout the concrete.

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<u>Storage:</u> Thirty days after completion of our studies, samples will be discarded unless the client submits a written request for their return. Shipping and handling fees will be assessed for any samples returned to the client. Any hazardous materials that may have been submitted for study will be returned to the client and shipping and handling fees will apply. The client may request that WJE retain samples in storage in our warehouse. In that case, a monthly storage fee will apply.

Photo 1: The fracture surface of Core 9 is shown. Dirt and debris are present all along the surface.

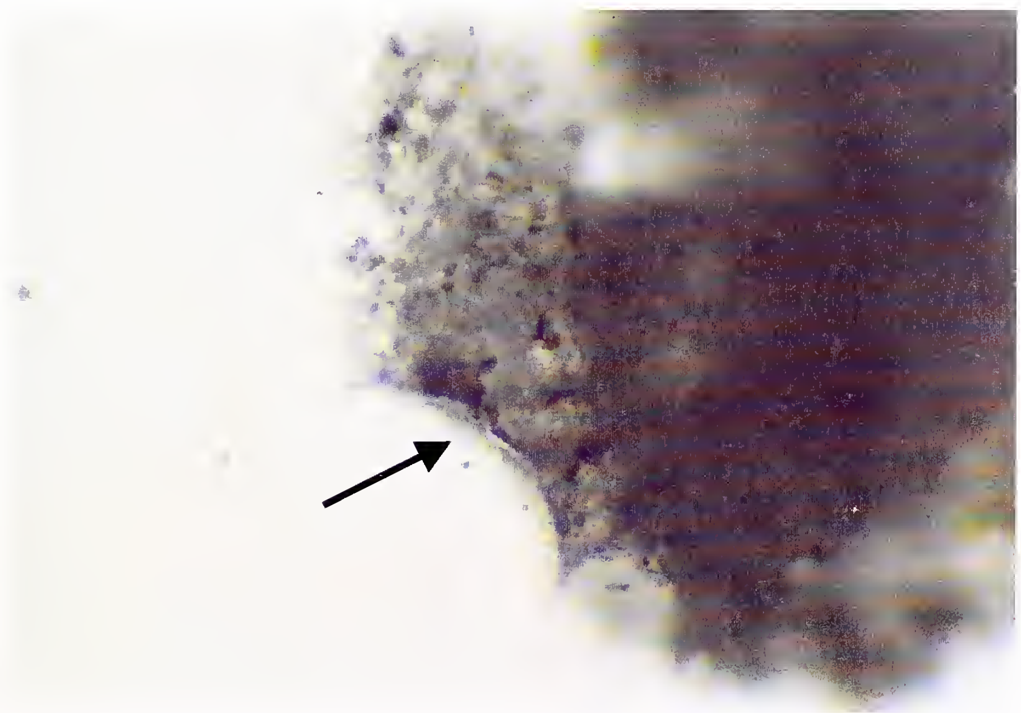

Photo 1: A grain mount of the cementitious material in Core 15 is shown. The arrow indicates ettringite needles, within an air void.